

# APPLICATION OF ACOUSTIC EMISSION TO MONITOR DAMAGE IN KEVLAR/EPOXY COMPOSITES

A Thesis Submitted  
in Partial Fulfilment of the Requirements  
for the Degree of  
**MASTER OF TECHNOLOGY**

REPORT

By  
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to the  
DEPARTMENT OF MECHANICAL ENGINEERING  
**INDIAN INSTITUTE OF TECHNOLOGY, KANPUR**  
FEBRAUARY, 1988

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### CERTIFICATE

This is to certify that the thesis entitled, "APPLICATION OF ACOUSTIC EMISSION TO MONITOR DAMAGE IN KEVLAR/EPOXY - COMPOSITES", by Lt. P.K. Gupta is a record of the work carried out under our supervision and has not been submitted elsewhere for a degree.

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### ACKNOWLEDGEMENTS

I express my deep sense of gratitude to my thesis supervisors Prof B. D. Agarwal and Dr. N. N. Kishore for their valuable guidance, constant inspiration and encouragement during the course of present work.

I am deeply grateful to Dr Sanjay Gupta for his valuable suggestions, help and interest in my work.

I wish to express appreciation to my friends K.K. Bajpai, Bharat Bhushan, P.V. Kishore, Vinay Kumar, C. Diwakar, H.R.N. Murthy, D.S. Rajan, B.G. Reddy, Lt. D. Ravi Kumar and others with whom I shared many ideas.

I wish to acknowledge the facilities at Materials Testing Lab of the Advanced Centre for Material Sciences and Experimental Stress Analysis Lab of Mechanical Engineering Deptt and the assistance of Messrs B. K. Jain, Swaran Singh, D. K. Sarkar, S. L. Srivastava, B.D. Pandey, P. N. Pandey and Avinash for their persistent efforts towards several requirements of present work.

I wish to recall the efforts of my parents in bringing me up to this level. A record of appreciation is due to my wife Alka for her constant encouragement and cooperation and daughter Meha for keeping a cheerful environment at home.

Finally I wish to thank all those, whose association

helped me directly or indirectly in accomplishing the present work and during the course of my program at IIT, Kanpur.

- Lt. P. K. Gupta

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## ABSTRACT

Acoustic Emissions are sound waves produced by rapid stress variations, caused due to various internal local failures within a material. Since composites are heterogeneous and failure mechanisms are complex, monitoring of acoustic emission can be an effective method for detection of defects, as they arise, in these materials.

The present work is an attempt to determine the proper test procedure for the acquisition and analysis of AE data. The AE data recorded in real time on 'AET 5000 Microcomputer based AE monitoring system' is available in the form of events listing. A computer software has been developed for data reduction as desired for specific interpretation and analysis. The software developed helps in obtaining the data in graphical form in terms of histograms and/or crossplots. Attention is placed on determining the methodology for an analysis with an end aim of establishing correspondence between AE event intensities and specific failure processes.

Preliminary investigations have been carried out on Kevlar fabric reinforced epoxy resin composites, fabricated in the laboratory by hand layup technique. Different laminate configurations considered are  $[0_{12}]$ ,  $[45_{12}]$ ,  $[90_{12}]$ ,  $[0_3/90_3]_s$ ,  $[90_3/0_3]_s$ . The specimens were subjected to static tensile tests on a 10 tonne MTS model 810 materials testing system and the AE data was recorded on AET 5000 system. It has been observed that

the analysis of various AE intensities can be useful in studying the type and zone of failure, which can be used for the prediction of impending failure.

## CHAPTER 1

### INTRODUCTION

#### 1.1 GENERAL INTRODUCTION :

Composite materials, principally the fiber reinforced ones, continue to replace metals in an increasing number of applications due to their high strength and stiffness coupled with low density. Better methods of producing and testing composites, enable these lightweight and chemically resistant materials to be used in more critical applications. Today, fiber composites have found such diverse applications as space vehicles, aircrafts, offshore structures, automobiles, sporting goods, electronics etc. The use of composite materials in vital structural applications requires reliable testing methods for their essential characterization and damage monitoring in these materials. Risk avoidance drives the need for advances in non-destructive testing (NDT).

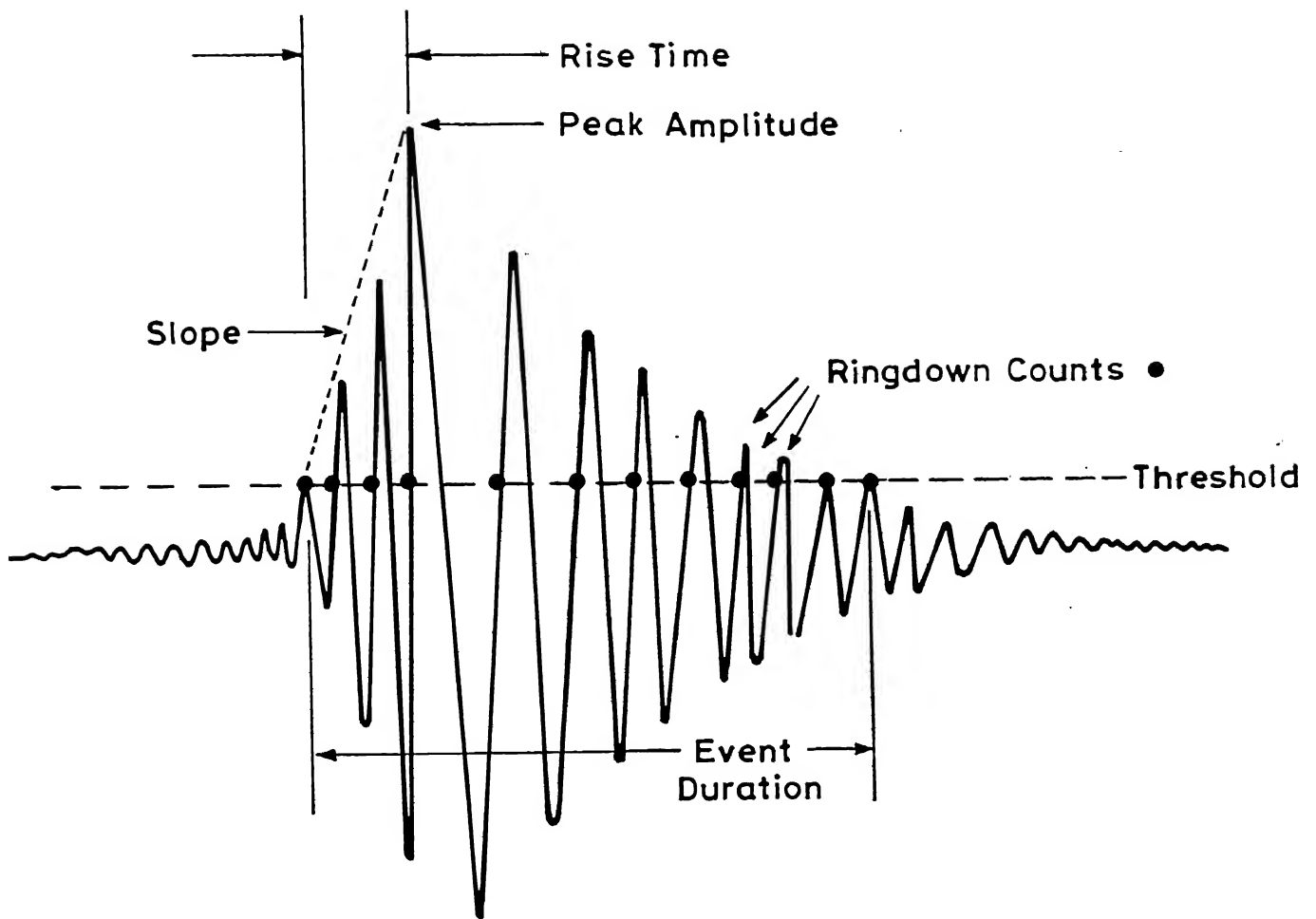
Composites, because of their heterogeneous structures, defy several standard NDT methods commonly used with homogeneous materials such as steel and aluminum. Radiography is unlikely to find a network of microcracks or debonds. Most of the polymer matrix composites are non-conducting, therefore, eddy current and magnetic particle inspection are ineffective. Ultrasonics (high frequencies used with metals) may not get through a laminate or may not produce a clean echo. Methods that are useful and applicable to composites include low frequency ultrasonics, sonics, acoustic emission, thermal imaging, moduli determination

and optical methods [1].

Acoustic emissions (AEs) are sound waves produced by rapid stress variations within a material. Monitoring of these sound waves (AEs) and their analysis has proved to be an effective testing method for tracking of damage progression in a material.

AE tests involve attaching of transducers (known as sensors in AE terminology) to the surface of a sample or structure which pick up the AE signals. The sensors are connected to preamplifiers, filters, postamplifier and the processing unit for signal amplification and conditioning. The sample or structure is loaded and the AE events are quantified. A typical AE signal is shown in Fig 1.1 which also lists out the various AE parameters.

Whenever stress or temperature fields are applied to a composite material, elastic energy gets stored in the material. Whenever internal local failure occurs there is a sudden release of such energy causing AE. In fiber reinforced composites it is due to multiple and complex local failures in the form of matrix cracking and splitting, fiber matrix interfacial debonding, fiber breaks, interlaminar delaminations etc. Composites are generally very noisy. AE from a fiber reinforced composite material is of significantly larger amplitude than that from a metal. This property of fiber reinforced composites makes AE testing an effective method for detection of defects, as they arise, in a composite specimen during a test or a composite structure during



SLOPE : PEAK AMPLITUDE DIVIDED BY RISE TIME

ENERGY: PEAK AMPLITUDE SQUARED MULTIPLIED BY EVENT DURATION

Fig.1.1 A typical acoustic emission signal.

its natural loading.

## 1.2 STATE OF THE ART :

AE and microseismic activity are naturally occurring phenomena which have been observed by man from early times. Although it is not exactly known when the first AEs were detected, fracture processes such as snapping of twigs, the cracking of rocks and the breaking of bones were no doubt among the earliest. But the first AEs noticed by an artisan or a craftsman, by which some message was conveyed about the material with which he was working, may well have been in pottery-making. Potters observed the sounds of cracking of clay vessels cooling too quickly in the kiln. These were audible AEs by which the potter knew his creations were defective and structurally failing.

Observations of audible sounds emitted by metals were, however, the starting point of extensive study in the field of AE. In as early as 1916, Czochralski [2] reported *Zinn- und Zinkgeschrei* (tin- and zinc-cry) as acoustic phenomena associated with twinning. The first experiment instrumented specifically to detect AE was conducted in Germany and published in 1936 by Foster and Scheil [3]. This was followed by two more experiments [4,5] in United States and England. But these instrumented experiments were not directed at the study of AE phenomenon itself.

The genesis of today's technology in AE was the work of Josef Kaiser [6]. In 1950 he reported the first comprehensive

investigation into the phenomena of AE. The objectives of Kaiser's research were to determine, from tensile tests of conventional engineering materials, what AEs are generated from within the specimen, the acoustic processes involved and the relation between the stress-strain curve and the frequencies noted for the various stresses. He concluded that the occurrence of AE arises from the frictional rubbing of grains against each other and also from intergranular fracture. His most significant discovery was irreversibility which now bears his name, the Kaiser effect. Kaiser effect is the irreversible characteristic of AE phenomenon resulting from an applied stress. That is, there is little or no AE until previously applied stress levels are exceeded. However, this effect later led to a number of seeming contradictions in the published literature on AE from fiber composites [7,8].

After Kaiser, large number of investigators initiated laboratory investigations into the AE phenomenon. In 1963 Dunegan wrote an internal report [9] proposing the application of AE techniques to pressure vessel research. The purpose of this report was twofold : First, to acquaint the reader with facts concerning the AE and second, to describe an approach being taken on practical applications of AE theory to pressure vessel research. These activities involved a broad spectrum of AE research and applications. In 1971, Pollock [10] directed his research towards the practical applications of AE for material testing and NDT.

The application of this testing technique to the field

of composite materials was suggested by Anderson and DeLacy [11]. While studying NDT of advanced composites they suggested AE as a method which should be investigated for its applicability to composites. In 1974, Hamsted [12] and Carlyle [13] examined the research and development applications that AE monitoring has for fiber reinforced composites. While Hamstad's work was a general and comprehensive guide to the use of AE testing in the research and development of composite materials, Carlyle placed specific emphasis upon obtaining information from fundamental failure processes in composites. His conclusions were mainly in the form of principles of the generation of emissions, the propagation of stress waves through materials, the production of electrical signals from mechanical stress waves and the signal processing to obtain data on microscopic sample deformations. Guild et al. [14] also examined the state-of-the-art with regard to the composite materials.

One of the most critical properties of any composite is the fiber-matrix interfacial bond strength, as this controls both the transfer of load into the reinforcing phase and the work of fracture of the composites. Arrington [15] used AE for debond tests in single fiber specimens. In these tests, single fibers were embedded in specially shaped resin specimens, which were tested in compression resulting in debonding. Because of its high sensitivity AE was chosen as the monitoring system. The AEs observed were directly related to debonding. Thereby determining the load at which the debonding starts and the severity of debonding as the load increases. This was then used to determine

the bond strength.

Ahlborn et al. [16] used AE as indicator for the beginning of crack propagation in notched specimens of unidirectional reinforced epoxy-resin during bending and tension tests. They observed AEs even when the areas of delamination or debonding were smaller than  $1 \text{ mm}^2$  and thus concluded that AE can be used effectively to indicate the beginning of crack propagation. Bunsell et al. [17] worked on evaluation of AE as a means of monitoring damage within composite materials. Their approach was to examine suitability of the AE technique for this purpose and to study the apparent problem areas. They observed that any deformation process within a material will result in stress wave emissions but this will only be a fraction of the total energy involved. Plastic strain, heating, the creation of new surfaces and frictional forces will all share in contributing to the total energy involved. The reflection at interfaces and at the boundaries of the specimens will further complicate the interpretation of the AE recorded at the surface. However, AEs can be used as an indicator of the damage within the composites.

Brown [18] investigated AE from specimens of glass reinforced plastics. His emphasis was on the use of AE for material assessment rather than for defect location. He conducted tensile tests on different specimens classified in terms of matrix type - epoxy or polyester, resin hardener ratio and density of square woven-roving reinforcement. He used ringdown counts as the parameter for his analysis. Conclusions took the form of empirical relationships based on the analysis of

adequate number of identical specimens.

AEs from a particular fiber composite made of different materials were studied by many investigators [19-26] with main thrust of these investigations being on monitoring damage initiation and accumulation through AE. Fitz-Randolph et al. [19,20] worked on AE studies of boron-epoxy composites. They found that AE can be directly related to the strain energy release rate.

Grandemange and Street [21,22] studied AE methods in boron-aluminum composites. They studied the possibility of utilizing AE methods to define the crack length changes. During tensile tests of notched specimens of the abovementioned material, a low frequency, about 20 kHz, accelerometer was coupled to a tape recorder as one method and a Dunegan/Endevco 3000 series AE monitoring unit, working in the 100 to 300 kHz band was used as a second method. In the preliminary experiments, the later set at a low sensitivity of 50 dB gave consistantly higher emission counts then the accelerometer. It was concluded using X-ray radiography and matrix dissolution techniques that the lower sensitivity accelerometer was detecting only fiber breaks. Fractographic examinations suggested that the higher frequency transducers were picking up events related to secondary fracture processes also such as fiber pullout, matrix-matrix interface failures etc.

Grenis and Levitt [23,24] while working on AE of graphite and boron fiber reinforced aluminum composites studied

the characteristics of fiber fracture in these materials. They used the conventional tension-test equipment to obtain stress-strain relationship for the material. This relationship was used to detect that region (strain) where significant fiber fracture was apparent to have begun and was compared with the corresponding AEs from that particular composite specimen. Kimpara and Takehana [25,26] investigated AEs from glass fiber reinforced plastic composites. The generating mechanism of the AE in the material was considered experimentally in conjunction with the failure mechanism of the material.

These studies used AE testing technique mainly to track damage progression in composite laminates in real time. Awerbuch and Ghaffari [27-29] directed their study towards discriminating friction generated emission from those caused by actual damage progression through a proper correlation among the AE event intensity variables. While working with graphite-epoxy specimens subjected to fatigue loading [28] and quasi-static loading [29] and while studying impact damaged composites [27], it was demonstrated that a significant amount of emission is generated by fretting among the fracture surfaces developed during loading. Consequently FRIction Emission Threshold values (FRET values) were defined such that the friction emission is all of intensities below FRET values.

Teti [30] worked to verify the possibility of identifying, during the fabrication process of composite material components, anomalies or non-conformities to production specifications purposely introduced in the fabrication cycle, by

means of mechanical testing and AE analysis. He found that structural alterations induced in the material by pressure variations during fabrication cycles may be identified through AE analysis. Mechanical parameters seemed incapable of producing significant and reliable information.

As can be seen, AE has been extensively used in the field of monitoring damage initiation and accumulation in a variety of material systems subjected to different loading functions. Results have demonstrated that AE technique is simple and very sensitive in detecting damage initiation and accumulation in real time.

The future scope of work lies in the identification of different failure mechanisms, determining damage criticality and subsequently establishing correspondance between AE event parameters (i.e. peak amplitude, energy, event duration, ringdown counts, location etc.) and the specific failure processes (such as matrix cracking and splitting, fiber breaking, debonding, delamination, fiber pull-out).

### 1.3 PRESENT WORK :

The present work is an attempt to determine the proper test procedure for the aquisition and analysis of AE signals. A computer program has been developed for postprocessing of AE data, recorded in real time on 'AET 5000 Microcomputer based AE monitoring system'. The accumulated data recorded during a test remains available to the user in the form of events listing. The software developed helps in obtaining the data in the form of

various histogram type displays and/or crossplots for data handling in such a way as is desired for specific requirements of data interpretation and analysis. A software approach for AE data reduction and analysis has been employed with an end aim of establishing correspondance between AE event intensities and specific failure processes. Attention is placed on determining the methodology for such an analysis.

A typical AE system consists of sensors, preamplifiers, band pass filters, main amplifier, processing unit, graphic display and recorder. Details concerning description of components, principle and working of AE system and the explanation of various AE terms are contained in chapter 2.

The present work concerns with the analyses of Kevlar fabric reinforced epoxy resin composite laminates. Different laminate configurations considered were  $[0_3/90_3]_s$ ,  $[90_3/0_3]_s$ ,  $[0_{12}]$ ,  $[90_{12}]$ ,  $[45_{12}]$ . Composite laminates were fabricated by hand lay up technique in the laboratory. Specimens of required size were obtained by sectioning the laminate with circular saw. These specimens were subjected to static tensile tests on a 10 tonne MTS model 810 materials testing system and the AE data was recorded on AET 5000 microcomputer based AE monitoring system. Fabrication of laminates and the experimental procedure have been described in chapter 3.

The software developed was used for the postprocessing of the accumulated AE data. The software description is contained in chapter 4. The discussion of results are presented

in chapter 5. Conclusions drawn and some suggestions for future work have been included in chapter 6.

## CHAPTER 2

### ACOUSTIC EMISSION AND ITS WORKING PRINCIPLES

#### 2.1 INTRODUCTION :

An AE, as mentioned earlier, is a transient elastic wave generated by the rapid release of energy within a material. This definition is broad enough to encompass events as gross as the final catastrophic failure of a structure and as small as the diffusion of one atom by one lattice position. In other words any material readjustment, internal or visible damage or phase transformation in any object produces AE. AE technology and its application focus on events that occur due to these developments in a material. AE technique can detect these internal releases of energy by using transducers to pick up the transient elastic waves. These signals can then be related to the physical integrity of the material, from which these are generated. Monitoring of these events permits detection and location of flaws as well as prediction of impending failure.

A typical AE signal, shown in Fig 1.1, lists out various terms used in AE testing. Few of these terms, viz. ringdown counts, peak amplitude, energy, event duration, rise time and slope are used as measures of AE activities, which help in characterization of an AE event. These parameters are known as AE intensities. By proper analysis of AE intensities detection of flaws and identification of the nature of flaw, is possible.

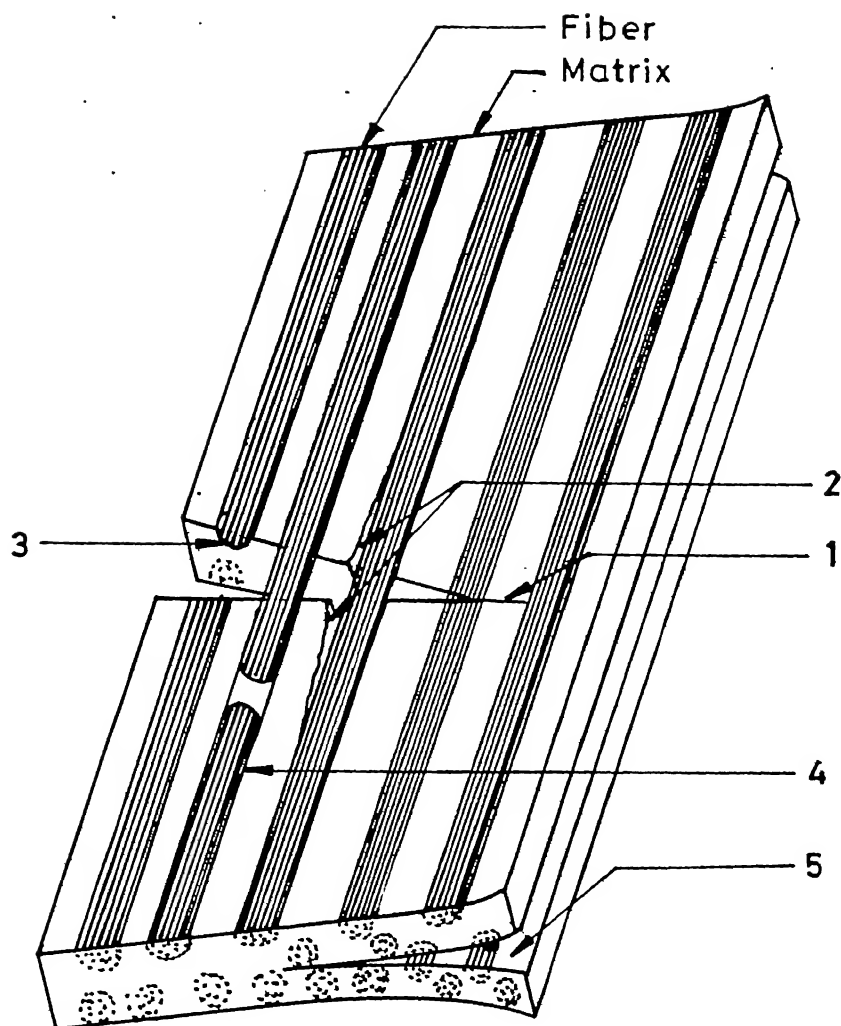
There can be various sources of AE in fiber reinforced composites as shown in Fig 2.1. Each of these sources of AE, that is each of these failure mechanisms has a characteristic AE. This can help in developing a suitable criterion, in terms of various AE intensities, for distinction of each of these failure mechanisms from the others.

Advantages of AE testing lie in its abilities of real time evaluation, continuous monitoring, detection of active defects, source location and its high sensitivity. Few disadvantages of AE testing are due to the difficulty in discrimination between noise and AE signals. AE testing needs a lot of experience before any attempt, towards the analysis of accumulated data, can be made.

## 2.2 WORKING PRINCIPLE :

Though the principle of AE testing is same for any application, this section concentrates basically on the present work and lays more emphasis on the working principle of AE testing technique as applicable to the present study.

The technique, as mentioned earlier, can be effectively employed for detection, identification and location of flaws and prediction of impending failure. Presence of AEs is, in itself, an indication of either a damage progression or the fretting between newly created surfaces, formed as a result of some damage. Characteristics of these emissions can be analysed for an information towards the identification of these damages. The location of a flaw or anomaly can be determined by using two or



- 1 Matrix Cracking
- 2 Fiber - Matrix Debonding
- 3 Fiber Break
- 4 Fiber Pull out
- 5 Delamination

Fig. 2.1 Sources of AE in fiber reinforced composites

more sensors. This is achieved by using the speed of the AE waves. A satisfactory determination of a representative speed of sound can usually be made by the calibration process described in section 3.3. The processor is then arranged to determine the difference in arrival times between the first sensor excited by the AE wave and each of the other sensors excited. The time difference (DT) and the order of arrivals are used to locate the source of the AE wave by triangulation using the formula :

$$\text{Distance} = (\text{Max DT} - \text{Actual DT}) * (\text{Sensor spacing}) / (2 * \text{Max DT})$$

$$\text{Location} = \text{Low sensor location} + \text{Distance, or}$$

$$\text{Location} = \text{High sensor location} - \text{Distance.}$$

Where, Max DT is the calibration DT.

AE testing necessitates conversion of AE to electrical signals, amplification, filtration and processing of these signals and display and recording of the processed signal. Block diagram of a general AE system is shown in Fig 2.2.

Detection of AE is accomplished by the sensor acting through a couplant. The sensors are attached to cleaned, dirt-free surface of a sample by the help of a suitable couplant. The couplant is used to fill in the air gap between the sensor shoe and the surface of the specimen and thereby couple the AE energy from the sample to the sensor. The couplant should be selected in such a manner that it does not corrode or wet the test surface or the sensor shoe. The sensors are, generally, piezoelectric crystals. In addition to piezoelectric sensors, electromagnetic, capacitive and optical sensors are also being used for different applications of AE testing technique. A typical AE sensor is

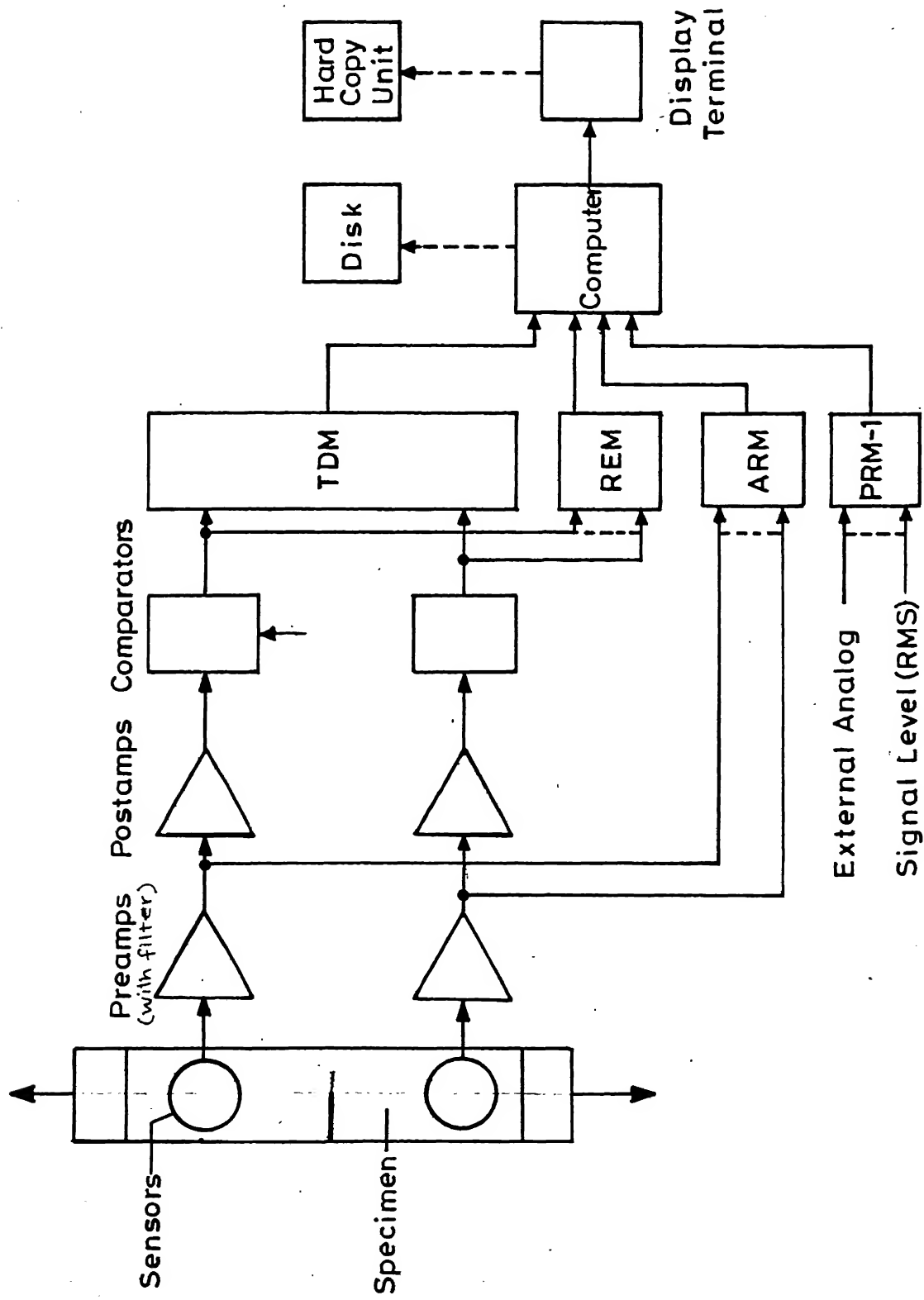


Fig.2.2 Block diagram of a general acoustic emission system .

shown in Fig 2.3.

The sensor is connected to a preamplifier. Preamplifiers are used to match high impedance of sensors to low impedance of sensor cables (low impedance cables pick up less airborne electrical interference) and to amplify the small sensor signals so that they may be handled by the usual electronic-signal-transfer techniques. The preamplified signal is passed through a band pass filter and the main amplifier with the objective to optimize the signal-to-noise ratio. Filters are used essentially to eliminate the background noise and transmit the signal in the desired frequency range. Background machine and personnel noise, with lower cut off frequency approximately in the range of 20 kHz to 50 kHz and electrical noise in the range of more than 1 MHz can be eliminated. The filtered signal is further amplified in the main amplifier. The overall amplification of the AE signal can be selected over a broad range.

From the main amplifier, the amplified signal is passed to a processing unit. The conditioned AE signals are processed in order to achieve one or more of the following objectives :

1. Accept AE signals of interest and reject all others.
2. Process the accepted signals and characterize the signals to determine the type of AE i.e. to determine various AE intensities.
3. Locate the source of AE.
4. Correlate the external analog parameters supplied by the users with the AE intensities. Analog parameters can be

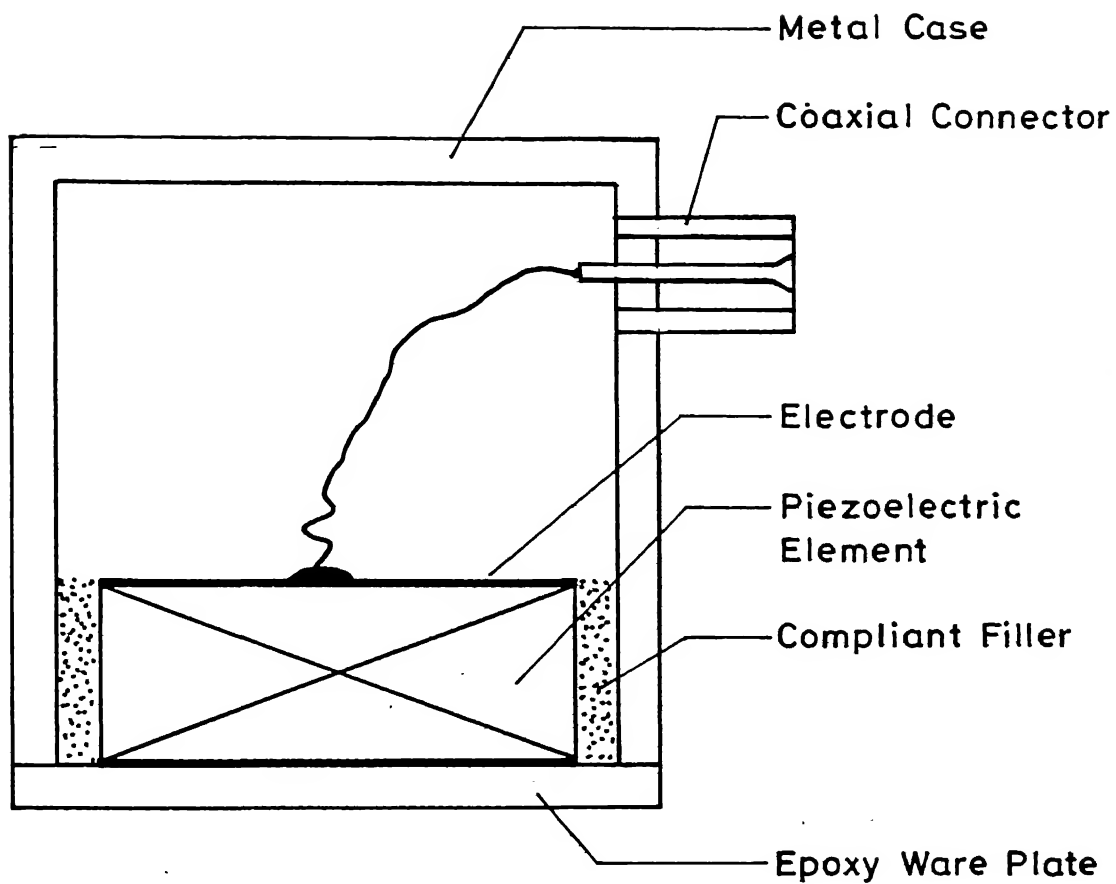


Fig. 2.3 A typical acoustic emission sensor.

stress, strain, displacement, temperature, pressure etc.

Micro-computer based systems are available for signal process instrumentation and one such system has been used in the present study.

The processed data is recorded for meaningful conclusion and future record. The data is then postprocessed to draw conclusions of specific interest.

### 2.3 BASIC SYSTEM AND COMPONENTS DESCRIPTION :

The AET model 5000, a computer based general purpose AE monitoring system comprising a computer automation LSI4/10 microprocessor, a graphic display terminal (IGT) and a Epson FX80 hardcopy unit connected to the GT through a composite video interface was used. The various components and their design features are described below.

**AE Sensors :** The standard AC 375 L sensors have a resonant frequency of 375 kHz and are omnidirectional, having a high sensitivity. The piezoelectric material is lead zirconate titanate contained in a chrome plated aluminum case and electrically isolated from the test structure by a non-conducting epoxy shoe which minimises ground loop problems. The sensors are 22 mm in diameter, 29 mm in height and weigh 26 gms. Couplant SC6 silicon grease, used for attachment of sensors to the surface of the specimen has excellent electrical insulating properties and has a flash point of 166 C.

**Preamplifiers :** The model 160B preamplifiers have a

gain of 60 dB and a flat frequency response between 1 kHz and 2 MHz. FL-25 filter is housed in the preamplifier casing.

Signal Processing Unit : The AET's model 208 signal processing unit (SPU) is a dual channel signal conditioner. SPU contains postamplifier, filter, threshold comparator and signal level circuits. This postamplifier and signal conditioner provides continuously adjustable gain from total attenuation to 40 dB. The SPU has signal level monitoring capability for continuous AE signals. The fixed or automatic (floating) threshold provides maximum discrimination between background noise and actual AE signals. Simple keyboard entries set threshold levels for any individual sensor in 0.01 to 10.0 Volts. To produce a digital AE signal, the SPU compares the fully amplified AE signal with the threshold. Whenever the AE signal rises above this reference voltage i.e. crosses the threshold the SPU produces a pulse which is sent to the system mainframe. By these pulses the mainframe can determine events, ringdown counts etc.

Incorporated within the system, the AE interface processes the digital and analog signals from the SPU. The interface is comprised of several modules which perform functions as needed.

Ringdown Counter / Event Duration Module : The ringdown counter / event duration module (REM) counts the number of threshold crossings in an AE event, counts the number of clock pulses to determine the event duration and supplies a control

signal to the amplitude / rise time module. The maximum value of ringdown counts that can be recorded by this module is 4095 and that of event duration is 65520 microseconds.

Amplitude / Rise Time Module : The amplitude / rise time module (ARM) measures the peak amplitude (in dB) of an event referenced to the fixed gain (60 dB) of the preamplifier. This module has a rise time clock also which turns on at the time of first threshold crossing and registers the time upto the occurrence of the peak amplitude. The processor operates on the peak amplitude / rise time data, determining the positive AE signal slope.

Time Difference Module : The time difference module (TDM) measures the difference in time of arrival of an AE wave at two different sensors. Thus one TDM is required for the linear location determination of AE sources whereas two TDMs are required for planer locations. Sensor locations can be assigned through keyboard entries.

Parametric / RMS Module # 1 : The parametric / RMS module # 1 (PRM1) is an analog-to-digital converter (ADC) which measures and digitizes the system power supply voltages, the signal level voltages and the three user supplied external analog voltages that may be associated with the AE test. These external voltages may represent such test conditions as stress, temperature, pressure etc. The input range is +/-10.24 Volts for the external parameters.

Computer : The main system computer is the Computer

Automation LSI4/10 stack oriented microprocessor. The AE operational program is entered from a disk drive of a North Star Advantage terminal. All software functions are preprogrammed to recognize the hardware configuration and respond to selected operator commands. Sufficient RAM memory is available to act as a storage area for real-time graphics displays and as a data buffer for incoming AE events.

Graphics / Display Terminal : The graphics / display terminal (GT) is a raster scan North Star Advantage terminal with both text (ADM-3 mode) and graphic (4010 mode) memories. The operator controls the system via commands entered on the GT keyboard. The GT has a real-time graphics capabilities. The intelligent graphics terminal is a separate, complete microprocessor. It works on CP/M system. The terminal is used for graphics display, keyboard input and data storage. AE data is recorded to disk on the North Star via a parallel interface from the LSI4/10 main system computer. The GT data displays may be hard-copied on the accessory Epson FX-80 dot matrix printer, connected to the GT through a composite video interface.

Hard Copy Unit : AET uses the Epson model FX80-FT dot matrix printer for both the line listing of the event data and the duplication of the displays on the Advantage's screen. This data is passed over a serial line from the Advantage serial port to the printer. The FX80-FT features 160 characters per second print speed, onboard storage of upto 256 characters, 80 columns, standard and reduced font characters. It uses standard one-part 9.5" x 11" tractor-feed paper.

The power supply to the system is conditioned by passing it through a voltage stabiliser and the spike buster. This provides a stabilised and noise free power to the system.

#### 2.4 EXPLANATION OF THE AE TERMS :

The various AE and associated terms used in the present study are briefly explained below as a ready reference to the present write up.

Acoustic Emission signal : The signal obtained by the detection of AE is known as Acoustic emission signal.

Threshold Crossing : Whenever an AE signal voltage exceeds a preset reference voltage (i.e. the threshold) a threshold crossing (TC) is said to have occurred.

Acoustic Emission Event : An acoustic emission event is the AE generated as a result of a local material change. An event is said to have begun when the AE signal amplitude exceeds the preset threshold for the first time and is said to be over when the next TC is not observed within the specified time gap (time gap is set so that if the gap between the two TCs exceeds this value, the former TC is considered as the last of the previous event while the later becomes the first of the new event).

Ring Down Counts : The number of times the AE signal amplitude exceeds a preset threshold during an AE event is known as the ring down counts of that event.

Event Count : Event Count is the number obtained by counting each AE event once.

Peak Amplitude : Peak amplitude is the measure of the peak signal in an AE event.

Event Duration : Event duration is the time measured from the first TC to the last TC of an event. It is thus, simply, the duration of an AE event.

Rise Time : Rise time is the time from the beginning of an AE event till the peak amplitude of the event is reached. It is measured from the first TC to the occurrence of the peak amplitude of an event.

Slope : Slope is the measure, as to how fast the peak amplitude is observed in an AE event. It is a software calculated parameter obtained as peak amplitude divided by rise time.

Energy : Energy, when referred in this study, is meant by the acoustic energy released by an AE event. This is another software calculated parameter calculated as :

$$(\text{Peak amplitude})^2 \times (\text{Event duration})$$

Arrival Time Difference : Arrival time difference (DT) is the time interval between the detected arrivals of an AE wave at two different sensors of a sensor array.

Acoustic Emission Intensity : Any of the several measurable qualities of AE signals from an active acoustic

source that may be used to grade the severity of the source can be called as acoustic emission intensity. Qualities that are measures of intensity are ring down count, energy, peak amplitude, event duration etc.

Decibel and Gain : Decibel is the log of a ratio. Gain is the measure of signal amplification. For a ratio of voltages we have :

$$\text{Gain (dB)} = 20 \text{ LOG}_{10} V_2 / V_1$$

Thus, an amplifier that produces one Volt of output ( $V_2$ ) for a one millivolt input ( $V_1$ ) has a gain of 60 dB.

## CHAPTER 3

### EXPERIMENTAL PROCEDURE

#### 3.1 INTRODUCTION :

The present investigations have been made on Kevlar-49 fabric reinforced epoxy resin laminates of different configurations. The specifications of Kevlar-49 fabric and that of epoxy resin, as supplied by the manufacturers, are given in Tables 3.1 and 3.2 respectively. Fabric has unequal counts and denier of fiber in cross-directions. This makes the fiber volume ratio in warp and fill directions as 10:1. This type of weaving is generally referred to as the unidirectional weave. Thus, wherever fiber orientation angle is mentioned in the present study, it refers to the warp direction which is the dense fiber direction.

#### 3.2 LAMINATE FABRICATION :

Composite laminates were cast between two 25 mm thick mild steel mould plates lined with mylar sheets, by hand lay-up technique in the laboratory. These mould plates are chromium plated to avoid rusting and thereby ensuring a good surface finish of the laminates. Twelve layers of fabric were used to obtain 3 mm thick laminates which had the configurations  $[0_3/90_3]_s$ ,  $[90_3/0_3]_s$ , and  $[0_{12}]$ . This gave a fiber volume fraction of over 52 % and a satisfactory surface finish.

First the fabric was cut into the required size, using the special Kevlar cutting scissors supplied by the manufacturers

TABLE 3.1 : KEVLAR-49 FABRIC SPECIFICATIONS

---

Product	-	Du Pont Co., USA
C. S. Style	-	343
Former Du Pont Style	-	143
Weight (per unit area of fabric)	-	190 g/m <sup>2</sup>
Tensile Strength,	warp	- 255700 N/m
	fill	- 28700 N/m
Count (Number of yarn per inch in warp x fill)	-	100 x 20
Yarn Denier (weight in grams of 30,000 feet long yarn),	warp	- 380
	fill	- 195
Weave	-	Crowfoot
Finish	-	CS - 805
Fiber Properties : Specific Gravity	-	1.44
Decomposition temperature	-	500° C

---

TABLE 3.2 : EPOXY SPECIFICATIONS

---

Product	-	CIBA Geigy India Ltd.
Category : Resin	-	Araldite LY556
Hardener	-	Hardener HY951 (10% of Araldite by weight)
Viscosity	-	5000 - 8000 cp
Pot Life	-	30 minutes to 1 hr
Specific Gravity	-	1.2-1.3
Tensile Strength	-	55-130 MPa
Tensile Modulus	-	2800-4200 MPa
Poisson's Ratio	-	0.20 - 0.33
Flexural Strength	-	125 MPa
Decomposition temperature	-	270° - 280° C

---

of fabric itself. The cut fiber was preheated to  $105^{\circ}\text{C}$  in an oven for 12 hours for complete demoiaturization and was then cooled in the oven itself so that no moisture could be absorbed again. The epoxy was also kept in the oven for a brief period for demoiaturization. The fabric was then arranged in order keeping in view the direction and side of the fabric. Lower mould plate was lined with mylar sheet and a layer of resin was spread over it. The first fabric piece was then put on top of the resin layer and another resin layer was spread on the fabric using a brush. A metallic roller, known as spatula, was used to roll and tap the fabric to ensure proper wetting and lamination. Similarly the rest of the fabric pieces were laid, with alternate layers being those of fabric and the resin. After the laying up of the complete laminate the top mylar sheet was placed and the laminate was rolled with the help of a rubber roller to squeeze out the entrapped air and the extra epoxy. The upper mould plate was then placed on the top. The thickness of the laminate was controlled by placing 3 mm spacers between the mould plates. The uniform tightening of nuts on the bolts, provided at the four corners and going through both the mould plates, ensures uniform pressure on the laminate.

The laminates were cured for 6 hours at room temperature followed by 12 hours at  $55^{\circ}\text{--}60^{\circ}\text{C}$ . Heating was performed through heating elements placed on the outer surface of each mould plate and the rate of heating was controlled through a transformer.

Volume fraction of fibers in the laminates can be

calculated using the following formula (since Kevlar fibers defy the standard resin burn-off test) :

$$V_f = (AN\rho_{fa}/\rho_f) / (A \times t) = (N\rho_{fa}) / t\rho_f$$

where,

- $V_f$  : Fiber Volume Fraction
- $A$  : Area of the Composite Laminate
- $N$  : Number of fabric layers in the laminate
- $\rho_{fa}$  : Areal Density of the Fabric
- $\rho_f$  : Density of the Fiber
- $t$  : Thickness of the laminate

In the present case we have,

$$\begin{aligned} N &= 12 \\ \rho_{fa} &= 0.190 \text{ kg/m}^2 \\ \rho_f &= 1.44 \times 10^3 \text{ kg/m}^3 \\ t &= 3 \times 10^{-3} \text{ m} \end{aligned}$$

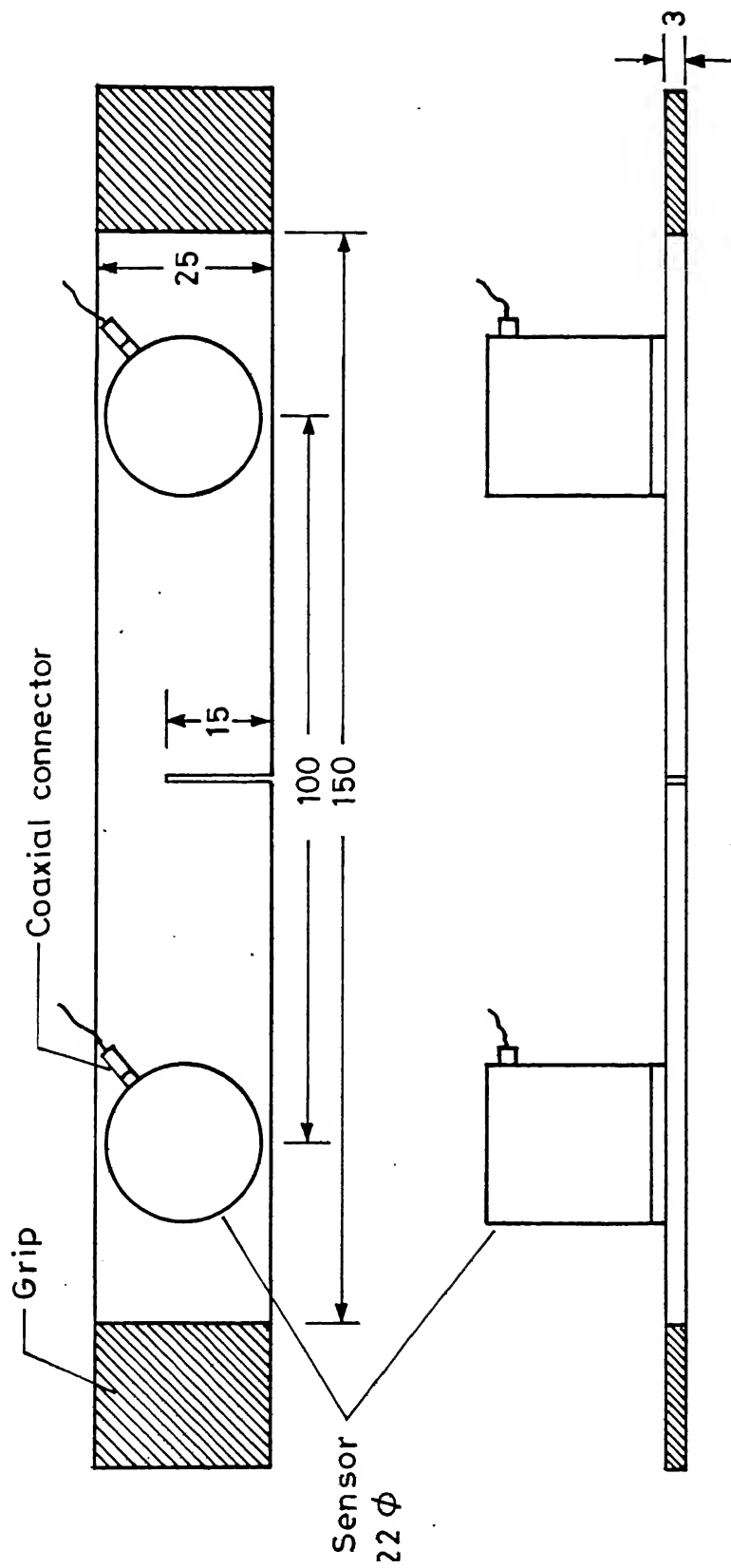
Hence,

$$V_f = 0.52777 \text{ ( = 52.8 \% )}$$

### 3.3 SPECIMEN PREPARATION :

Specimen preparation involves cutting of specimens of required size from the laminates, finishing of specimens and cutting of notches in these specimens.

Specimens of the dimensions, as shown in Fig 3.1, were cut from the fabricated laminates. From the laminate  $[0_{12}]$  samples were cut in such a manner so as to obtain specimens of  $[0_{12}]$ ,  $[90_{12}]$  and  $[45_{12}]$ . The other two laminates provided samples of configurations  $[0_3/90_3]_s$  and  $[90_3/0_3]_s$ :



All dimensions in mm

Fig. 3.1 Specimen geometry

The difficulties in mechanical cutting of Kevlar composites, are due to the fiber toughness. Because of its high toughness and strength, the fibers break and pull out from inside of the composites instead of cutting at the edge. This problem is more at low cutting speeds. Cutting by router at high speeds produces a lot of brooming at the edge whereas use of a low power laser beam burns off the edges.

The best results in cutting laminates were obtained in circular sawing when unconventional side (slant side of teeth) of a metal slitting fine toothed H.S.S. cutter was used at high speeds. This method was adopted for specimen preparations for the present investigations. Firstly two sides of laminate were cut and were trued to be used as reference edges and adjusting the width of the specimen on the cutter the specimens were cut. The quality of the edge was satisfactory except for few broomed fibers at the side of the edge from which cutter comes out after cutting, in case of  $[90_{12}]$  and  $[90_3/0_3]_S$  specimens.

The specimens were finished by rubbing them on wet waterproof emery paper. During finishing operations it was ensured that the specimens reduce to exact dimensions as per the requirements, the edges become perpendicular to each other and are trued perfectly and the brooming gets removed to give a good edge finish.

The specimens were then marked and nothes were cut in these. Notch cutting was done on the lathe and the a/w ratio (notch length to specimen width ratio) was kept as 0.6. All the

three operations, cutting, finishing and notch making were done with due care and the coolant was used in each of these operations to ensure a proper finish of the edges.

### 3.4 SETTING OF THE AET PARAMETERS :

During the performance of AE tests various settings which were fed through the keyboard entries are enlisted below.

For simplicity the distance between the two sensors, used in these tests, was divided into 100 segments for the purpose of monitoring the line location and these segments correspond to locations "0" through "100" in the location distribution histograms.

The preamplifier gain for both the sensors was set to a value of 60 dB (since the preamplifiers used with each of the sensors have a gain equal to this value). The threshold level was set at a value of 1 Volt fixed since the machine noise through grips and the other noise level was observed to be less than this value after mounting the specimen. Type of tests conducted was linear, with sensor numbers 1 and 2 having locations of "0" and "100" respectively. Maximum DT was initially set as 0 which gets automatically corrected to a value obtained during the course of calibration.

Clock period of event duration module was set as 125 ns and that of rise time module as 250 ns.

Ranges of different AE parameters were set to their default values itself and are as shown in Table 3.3. These

TABLE 3.3 : DISCRIMINATORY RANGES OF VARIOUS AE PARAMETERS

	MIN	MAX
Event Duration	0	65520
Ring Down Counts	0	4096
Rise Time	0	64520
Peak Amplitude	0	117
Slope	0	65520
Energy	0	165
Analog Parameters (# 1/2/3)	0	10230

ranges are used as a basis for the discrimination of selected and rejected events. These default values were selected so that all the events get recorded as selected events for a detailed analysis. The other alternatives for setting of these and various other variables are given in Reference 31.

### 3.5 EXPERIMENTAL PROCEDURE :

Basic characterization of the material was done by tensile tests of unnotched  $[0]_{12}$ ,  $[90]_{12}$  and  $[45]_{12}$  specimens on a 10 tonne MTS model 810 materials testing system, available in the Materials Testing Lab of the Advanced Centre for Material Sciences (ACMS). The material properties thus obtained are given in Table 3.4.

The notched specimens were then used for AE testing. The specimen surface was cleaned with acetone and made dirt-free. Two sensors were then attached to the specimen surface with their

TABLE 3.4 : ELASTIC CONSTANTS OF THE MATERIAL

---

Longitudnal Modulus ( $E_L$ ),	-	49.08 GPa
Transverse Modulus ( $E_T$ ),	-	12.88 GPa
Inplane Shear Modulus ( $G_{LT}$ ),	-	2.65 GPa
Major Poisson's Ratio ( $\nu_{LT}$ ),	-	0.193
Minor Poisson's Ratio ( $\nu_{TL}$ ),	-	0.051

---

NOTE : All properties are for the dense fiber direction

centres 10 cms apart and equidistant from the central notch. The sensors were attached with the help of couplant, SC6 silicon grease smeared on the shoe of the sensors in a light lyer. A paper tape was also used to ensure intimate contact between the sensor shoe and the specimen.

Firstly the calibration of the test was performed with each specimen to get a representative speed of sound in the specimen material. The calibration needs to be done in case of every distinct laminate configuration since the specimen geometry has an influence on this result. Calibration was performed by placing a standard AE source, in terms of another sensor which is connected to the mainframe's 5 Volts output pulses, at a small distance from one sensor, outside the 100 segments region. The standard AE source simulator sends out a signal of constant level. A constant output is more important than the actual level. This signal was picked up by the two sensors. The difference in arrival times of this signals at two sensors was used by the system computer to determine the representative speed of sound in the material.

The pulser was then detached and the specimen was mounted on MTS machine. Mounting was done in load controlled mode. Hydraulically operated grips of the machine help in the speedy insertion and removal process of the specimen in addition to providing excellent axial and angular alignment.

Tensile test was performed upto fracture, in stroke controlled mode and the AE data was recorded on AET 5000 microcomputer based AE monitoring system. Load and displacements were recorded on AET 5000 system as external analog parameters 1 and 2.

The various test parameters were:

Load            10% (1000 kgs)    i.e. 10 Volts = 1000 kgs

Stroke        10% (10 mm)            i.e. 10 Volts = 10 mm

Specimen length between grips        15 cms

Time for test            10 mins in Stroke controlled mode

Fig. 3.2 and 3.3 show overall views of the specimen under test on MTS and AET 5000 AE monitoring system. Fig 3.4 shows the damage zone in the samples of different configurations.

The accumulated AE data was postprocessed using the software developed as will be explained in next Chapter.

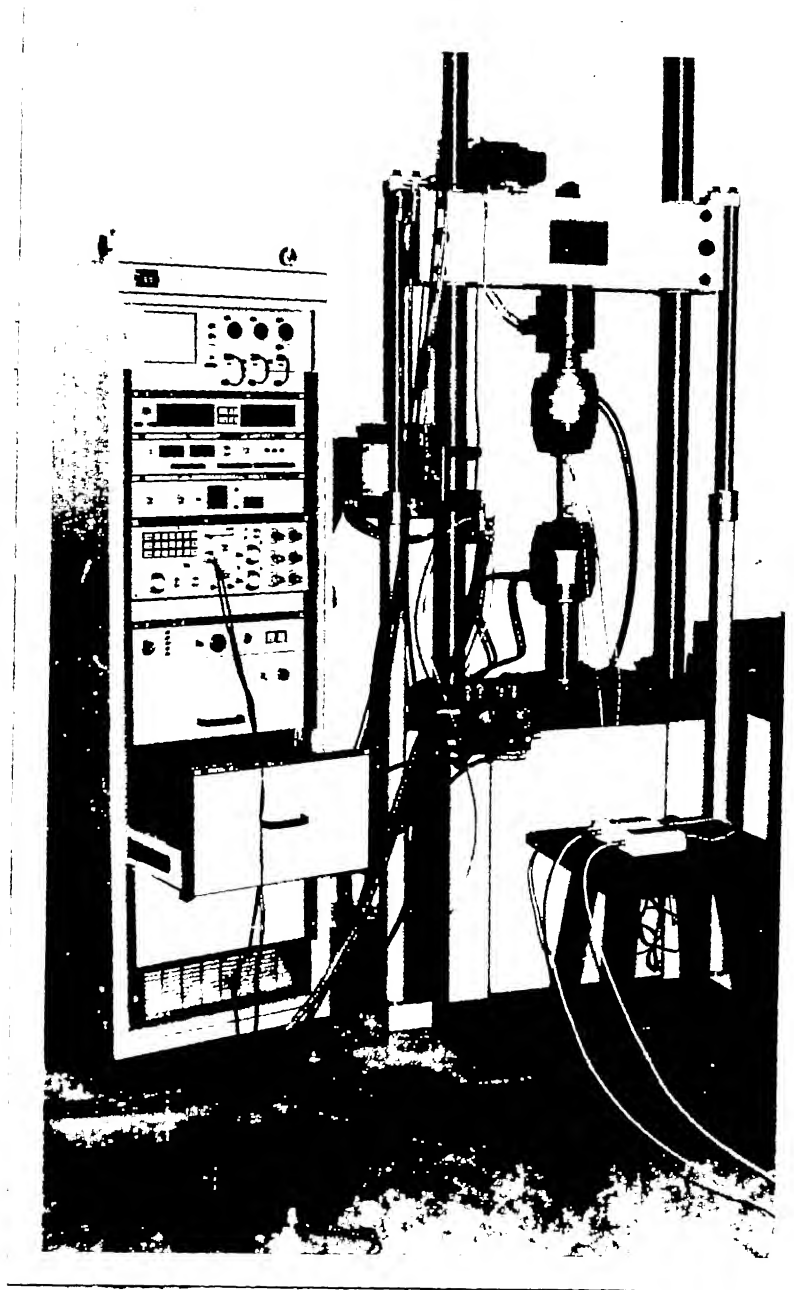


Fig. 3.2 An overall view of specimen under test  
on MTS.

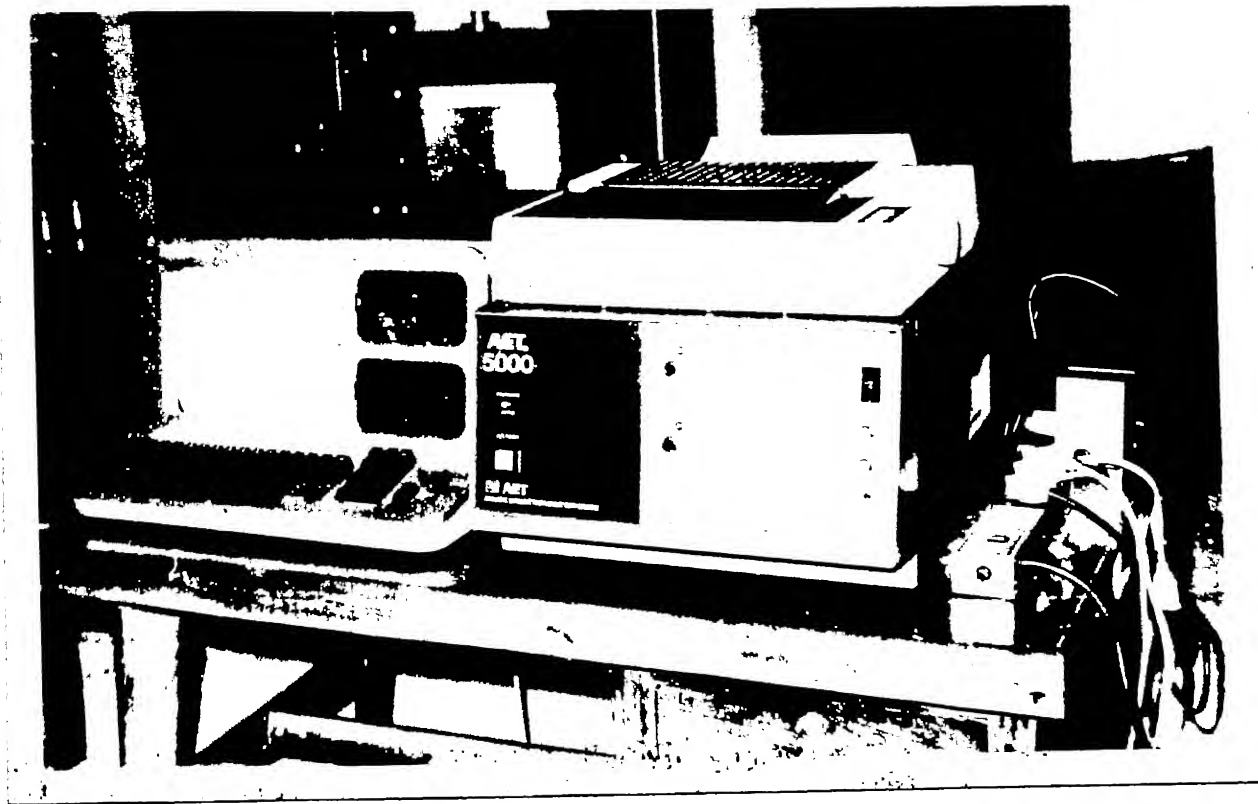


Fig. 3.3 An overall view of AET 5000 AE monitoring system.

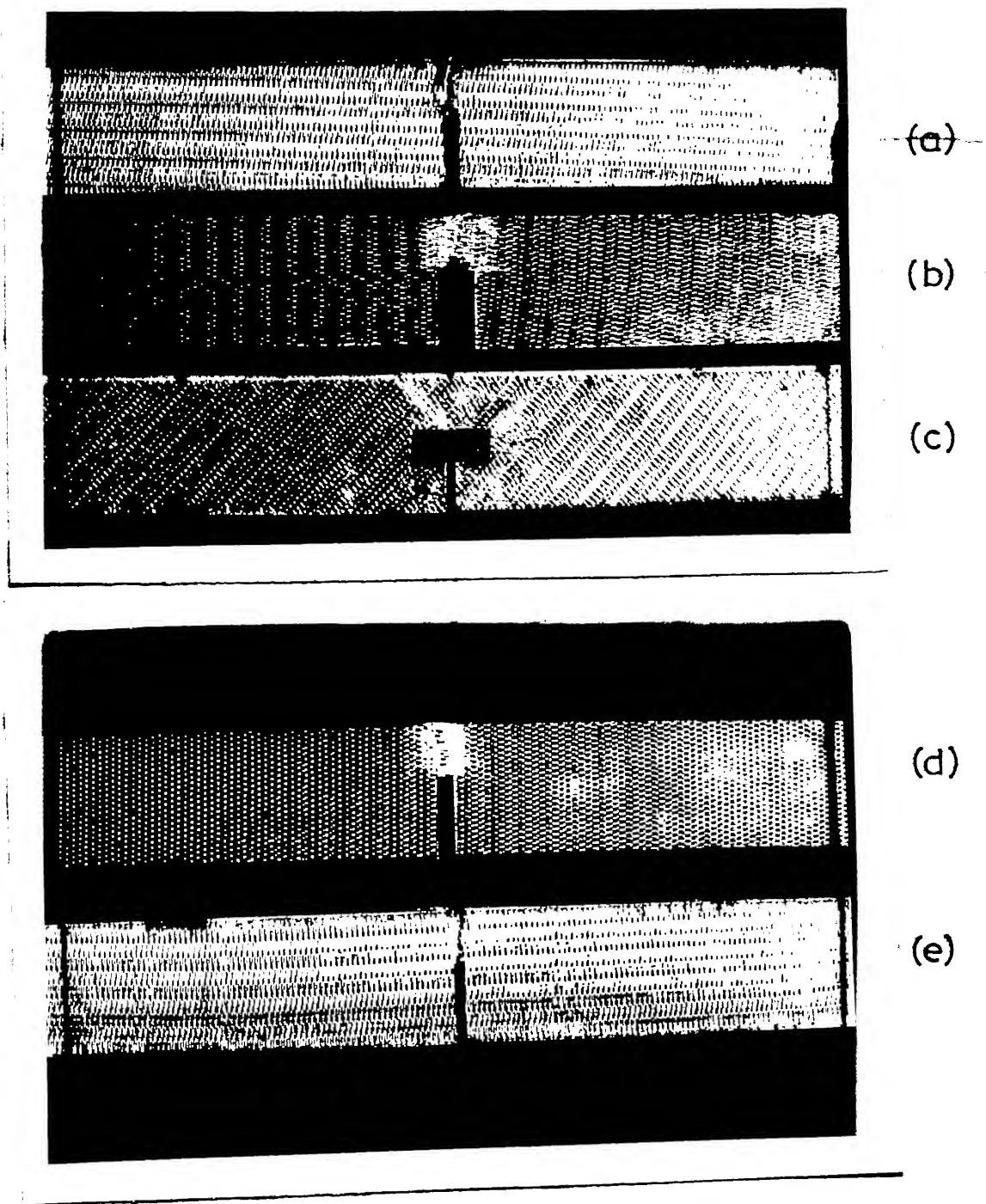


Fig. 3.4 Damage zone

- |                        |                           |
|------------------------|---------------------------|
| (a) $[90_{12}]$ sample | (d) $[0_3/90_3]_S$ sample |
| (b) $[0_{12}]$ sample  | (e) $[90_3/0_3]_S$ sample |
| (c) $[45_{12}]$ sample |                           |

## CHAPTER 4

### SOFTWARE DESCRIPTION

#### 4.1 INTRODUCTION :

The North Star Advantage graphics / display terminal, supplied by AET as the system terminal for the AET 5000 system, is a 8-bit computer with 64K bytes of RAM and bit-mapped graphics. It has a real-time graphics capability for the purpose of data reduction and analysis in real-time. Displays set by the user, before a test run is conducted, are continuously updated during the run. Displays can also be set during a run, but only the data occurring after the time of selection of such display will be posted in real-time. Graphics display on the North Star is done by the LSI4/10 computer in the 5000 mainframe. After loading the main program into the system (about 32K of RAM required), the remaining RAM (32K) is available as a storage area for the real-time graphics displays and as an incoming data buffer for AE events.

The real-time graphics capability of AET 5000 system, however, does not eliminate the need for a detailed postprocessing tool, in terms of a suitable software, for handling of accumulated data at a later stage. The necessity for development of a software, for this purpose, was further enhanced due to various other reasons as will be explained later.

The Advantage has a common memory which is shared graphics and alpha-numeric information requirements. Setting

real-time displays, use of 'OUTPUT EVENTS' routine, calling up of displays, all these fill up the available memory, to an extent depending on the quantum of memory requirement for each of these. This may result in loss of some of the unprocessed events since the processor discards the data during the periods when the buffer memory is full. To eliminate or reduce the number of 'LOST EVENTS', setting of only a minimum number of real-time displays is essential. This gives rise to the requirement of some means of obtaining the accumulated data in the form of displays after the test run is over.

The needs, in terms of the format of data presentation, are different for different type of works and analyses. No one program can have the capabilities to satisfy all of these needs. This holds even in the case of real-time display capabilities of AET 5000 system. For instance, AET 5000 real-time display capabilities do not include data presentation in the form of crossplots. A software development, therefore, became essential to accomplish specific tasks required for this study and to assist in some way in the future work proposed, on the subject, at this institute.

#### 4.2 POSTPROCESSING PROGRAM FEATURES :

AET Corporation has provided two softwares POSTPRO and USERPRO to provide the user of the AET 5000 system with the ability to do postprocessing of accumulated data in a stand-alone environment.

USERPRO is a 'Skeleton Program', provided by the AET,

as a means for users of AET 5000 to access and process AE data stored on the disk. This core program allows the user to write a CBASIC program to manipulate the data and serves as a starting point for the development of software for the specific data analysis purposes. The main purpose of this code is to provide the basis to create a postprocessing package for specialized applications.

The program, as supplied by the system manufacturers, contains the necessary code for reading the AET data files. It generates one form of output in the form of events listing. It also lists on the screen any sensor or test parameters encountered on the disk. The program prints out the events, as on the disk file, in the order they were generated. It does not offer the option to select which sensor or test events should be printed and prints all selected as well as rejected events.

The description of AET 5000 data file format, method of data retrieval by the use of this code and the detailed description of this code are contained in Reference 32. The facilities that are lacking in this code include performing any desired calculations on the data and/or produce any sort of output, including graphical output.

The POSTPRO program running on the North Star microcomputer alone is capable of creating crossplots and drawing 5000-type displays. The program code, however, seem to have an error in declaration of some array because of which it could not be used to draw 5000-type of displays. The code of this program

was not provided, thereby disabling the user to handle the error and to rectify it. This, along with the specific requirements of data reduction and analysis, rendered this software insufficient and unsatisfactory for the proposed work.

All these factors gave rise to the requirement for development of a software which can handle the accumulated AE data in the desired fashion.

#### 4.3 DESCRIPTION OF THE SOFTWARE DEVELOPED :

The basis of the developed software "USERNEW" is the skeleton code, in the form of USERPRO, which is used for retrieval of the AE data stored on a North Star Advantage disk. The program is capable of presenting the accumulated data in the form of 5000 type of displays and/or crossplots. In these broad categories, several options are available to meet certain specified requirements. The program can also serve as a basis for further expansion so as to include additional features to increase its versatility.

In its present form the program offers the following options :

1. 'OUTPUT EVENTS' - Type Event Listing
2. 5000 - Type of Displays
3. Crossplots

In the beginning the user has to specify the data file name in response to a prompt asking for it. The user can then choose any one of the above options. The program offers only one option during a run. If two or all the three options are selected the

software disallows it and asks to choose the options again. Any test or sensor parameters, encountered while reading the specified data file, are then displayed on the screen, irrespective of the selected option. This includes the discriminatory ranges of various AE parameters for any test or sensor.

If the first option is selected, USERNEW simply reads the AE data from the specified file, available on a disk. For each of the events read from the disk, energy, slope, location, region and event time are calculated. Depending on the discriminatory ranges the events are then classified as selected or rejected events. Selected events are printed with a '#' sign in the first column while the rejected events have a '%' sign in the first column. The events listing can be used to study the statistical characteristics of the data and/or for a general survey and overview of material behaviour during the test, to which this data belongs.

The extension of the original USERPRO code, however, was aimed at achieving the other two options. In case of both these options the program runs twice. During the first run the maximum and minimum values of parameters, that form one of the axes of any of the displays set are determined by screening of the entire data. During this run itself the maximum value of load (i.e. analog parameter # 1) is also determined in case window is desired by the user, load being the criterion for windowing. These value are used in the second run to plan the axes and for the division of X axis in the desired number of

intervals for the 5000-type of displays (histograms).

The program structure is such that in case of option 2 or 3 the user has to reply certain prompts to set desired displays in the desired fashion depending on the program capabilities. The various options available to the user and the possible replies to various prompts encountered during the USERNEW execution are shown in detail in the flowchart placed at Appendix A. A sample dialogue is placed at Appendix B. The AE data is read from the specified file. Calculations of parameters like energy, slope, location etc. and discrimination between selected and rejected events is done as in the case of option 1. On reading each individual event, its parameters are transferred to a subroutine and are stored there in an array called PLOTDATA. The parameters from this array, that need to be plotted are compared with the previous corresponding maximum and minimum values and the resulting maximum and minimum values are determined and stored. Parameters of the next event, as read from the disk, replace the old values in the array PLOTDATA and are again compared in the same manner. Thus at the end of this run the maximum and minimum values of all the relevant parameters are registered in the computer memory.

If option 2 is selected, the maximum and minimum values of the X axis parameter are displayed for each of the displays set. Then the user can set the number of intervals, the interval size and the minimum value for plotting of the X axis variable for each of the displays for the purpose of planning the histograms. If distribution of events at different load levels

is set the maximum value of load is also displayed which is used by the processor to set the windows as per the required load levels. At this stage the second run begins and the data is read again. The event parameters are again passed to the same subroutine for getting stored in the same array. Selected events not corresponding to the test or sensor for which the displays are set are discarded. Similarly the events not corresponding to the regions for which the displays are set are also discarded. The relevant events are processed and are put in bins, created by the division of X axis based on the information supplied by the user in terms of the number of intervals, interval size and the minimum value of the X axis parameter. The calculations for different options of the Y axis variable are different for the purpose of incrementing the bins. e.g. in case of any analog parameter as a Y axis variable the mean value of the entire data of each bin is calculated whereas in case of distribution of events being the Y axis variable the value for a particular bin is incremented by one with every event falling in that bin.

When all the events get processed and the histogram dimensions are determined and stored in the memory the user can call any of the set displays for display at screen. Firstly a heading is displayed and the axes are drawn on a convenient, uniform and rational scale based on the maximum and minimum values of the parameters corresponding to these axes. The axes are divided in rational intervals to provide a good readability. finally the histograms are plotted on the drawn axes. Any display can be called for display on the screen any number of

times and can also be hardcopied.

The program presently offers three displays during a run, each one of which can have a maximum of fifteen bins. However these values can be increased by minor modifications in the software. In case of a display of distribution of events at different load levels against any AE parameter, four different load percentages can be set for each of the three possible displays, one of which has a fixed setting of hundred percent of load. This can also be changed using simple modification to the existing software.

In case of option 3, during the second run the axes are firstly plotted using the maximum and minimum values of the X and Y axis variables. A heading is then displayed and the events corresponding to the concerned test or sensor and the region are plotted, on the drawn axes, as these are read. Only one crossplot is possible during a run since it involves direct plotting of events, as they arrive, on the screen. The crossplots in form of line drawing can also be obtained by setting, line drawing on, while setting the crossplot. Line drawing plots are essentially like crossplots except that a line connects each successive point in time order.

The extended code for the inclusion of the above mentioned features was entered using the document mode of wordstar. Editing of the skeleton program, in the form of USERPRO, for certain deletions and alterations was also done with the help of wordstar itself. The page breaks introduced by the

wordstar were removed with the help of a utility program PAGE.COM. The edited version was compiled using the program BASIC.COM supplied by the AET. The location address of assembly language routines, used with this software, were changed to create sufficient memory space for the developed software. Since the graphics capabilities are included in the software, the North Star graphics manager was appended to the file RUN.COM, which is used for the execution of the CBASIC programs. Appending of graphics manager was achieved using a program GMGRADD.COM.

The compiled version of this software can be executed using a command RUN USERNEW. When the data file name is asked, the disk containing the data file should be mounted and the name of the file should be supplied through the keyboard. Since CBASIC will not read the binary files the data from the file is read with the help of an assembly language program FILEOPS. Thus before the second run can commence, the processor asks to load the disk containing the FILEOPS followed by another instruction to load back the data file. The access to the North Star graphics manager is provided by another assembly language routine known as GRAPHICS. All it does is load registers from a memory area set by the various graphics functions and call the graphics manager. A third assembly language program is also used known as LOADER. LOADER's function is to read assembly language program files into memory at an address specified in each file. The program can be halted at any time, while it is processing, by typing CONTROL-C.

In the present study the accumulated AE data from

various tests is postprocessed using this software. Thus the software has also been tested for adequate and meaningful postprocessing.

## CHAPTER 5

## RESULTS AND DISCUSSIONS

To understand the behaviour of damage propagation and the AE the following types of laminates were considered:

unidirectional laminates:  $[0_{12}]$ ,  $[45_{12}]$ ,  $[90_{12}]$

cross ply laminates :  $[0_3/90_3]_s$ ,  $[90_3/0_3]_s$

Fig. 5.1, 5.2 and 5.3 show the location distribution histograms for the three unidirectional laminates. As indicated earlier the sensors were placed equidistant on either side of the notch and they are assigned location 0 and 100. That is, the notch corresponds to a location of 50. It may be kept in mind that the reinforcement used was in the form of fabric which has fiber volume ratio of 10:1 in the warp and fill direction.

The histogram corresponding to 100% load represents that of ultimate failure load. From the three figures it can be observed at the time of failure the damage in case of  $90^\circ$ -laminate is localized around the notch; in the case of  $0^\circ$ -laminate it is confined to approximately 5 % neighbourhood; whereas in the case of  $45^\circ$ -laminate the damage is spread over an area of 10% around the notch. This can be explained as follows: in the case of  $90^\circ$ -laminate the crack propagated in a self similar manner without much obstruction and in the case of  $0^\circ$ -laminate as the fibers break and ensuing splits along fiber-matrix interface the damage is spread in the fiber direction; whereas in the case of  $45^\circ$ -laminate the crack propagation is along the 45-direction which corresponds to a damage over a wider

Kevlar-49 / Epoxy  
Ultimate load = 1166 kg

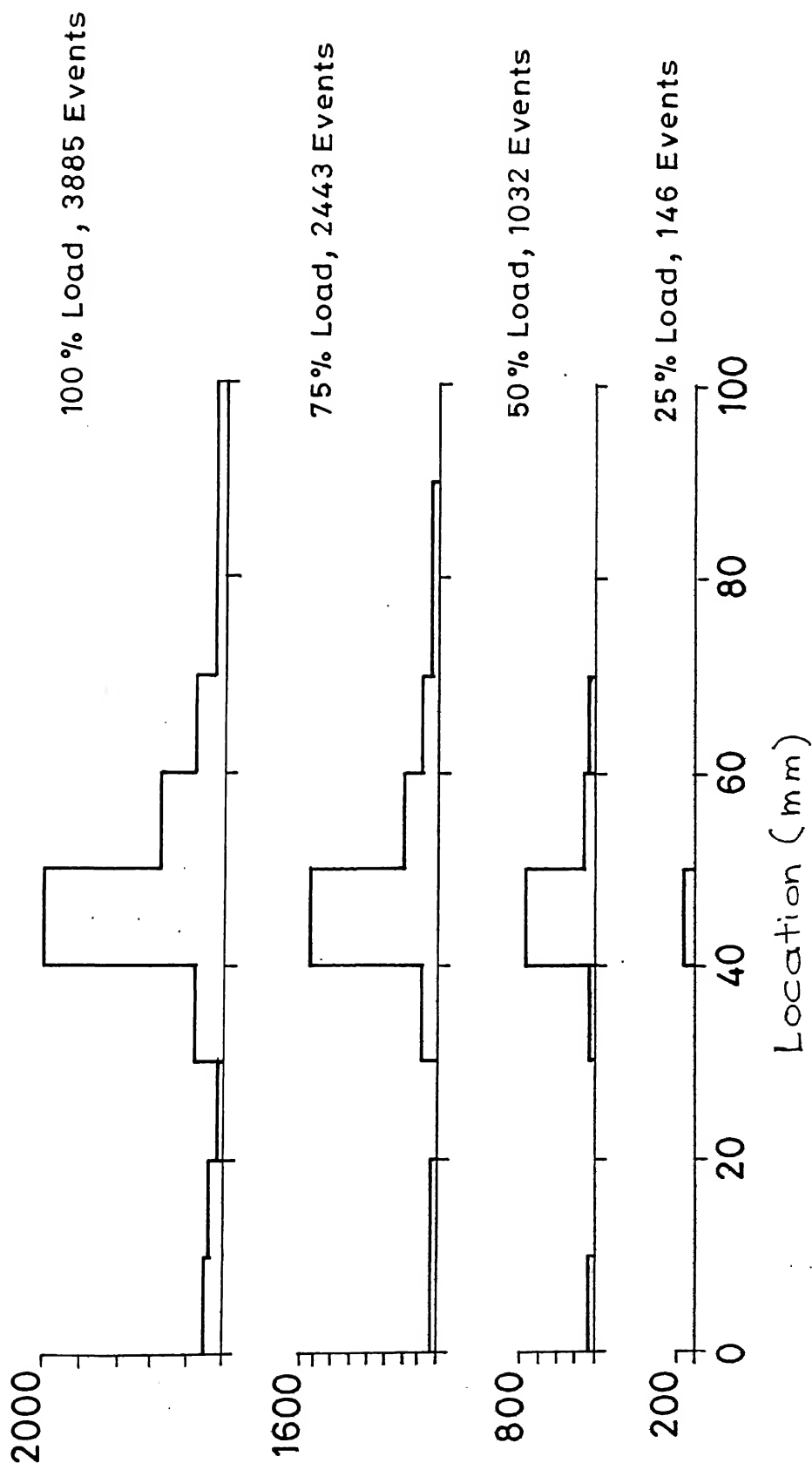


Fig. 5.1 Distribution of events vs location (LOC) of  
[0<sub>12</sub>] - laminate.

Kevlar -49/Epoxy  
Ultimate load = 148 kg

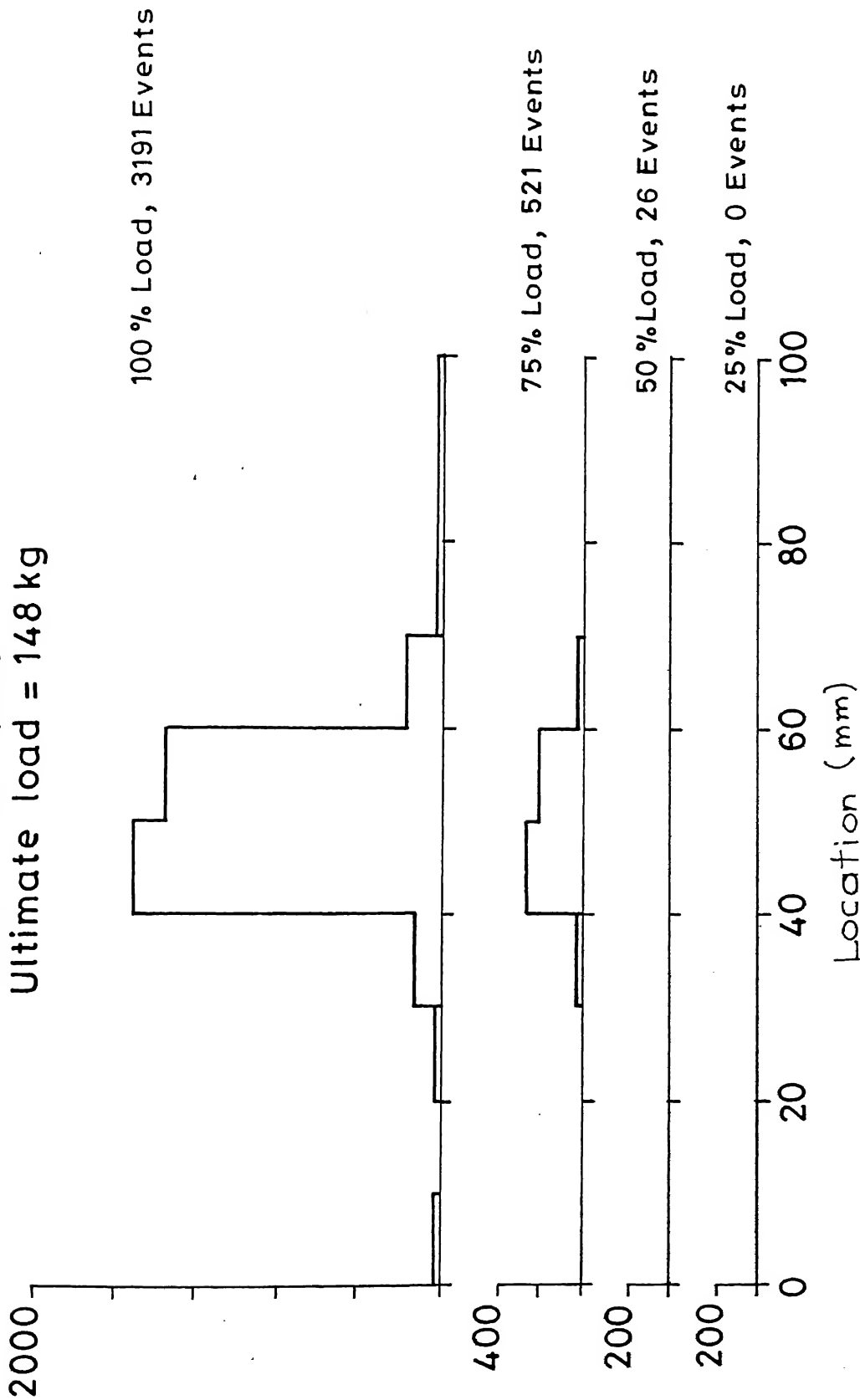


Fig.5.2 Distribution of events vs location (LOC) of  
[45<sub>12</sub>] - laminate.

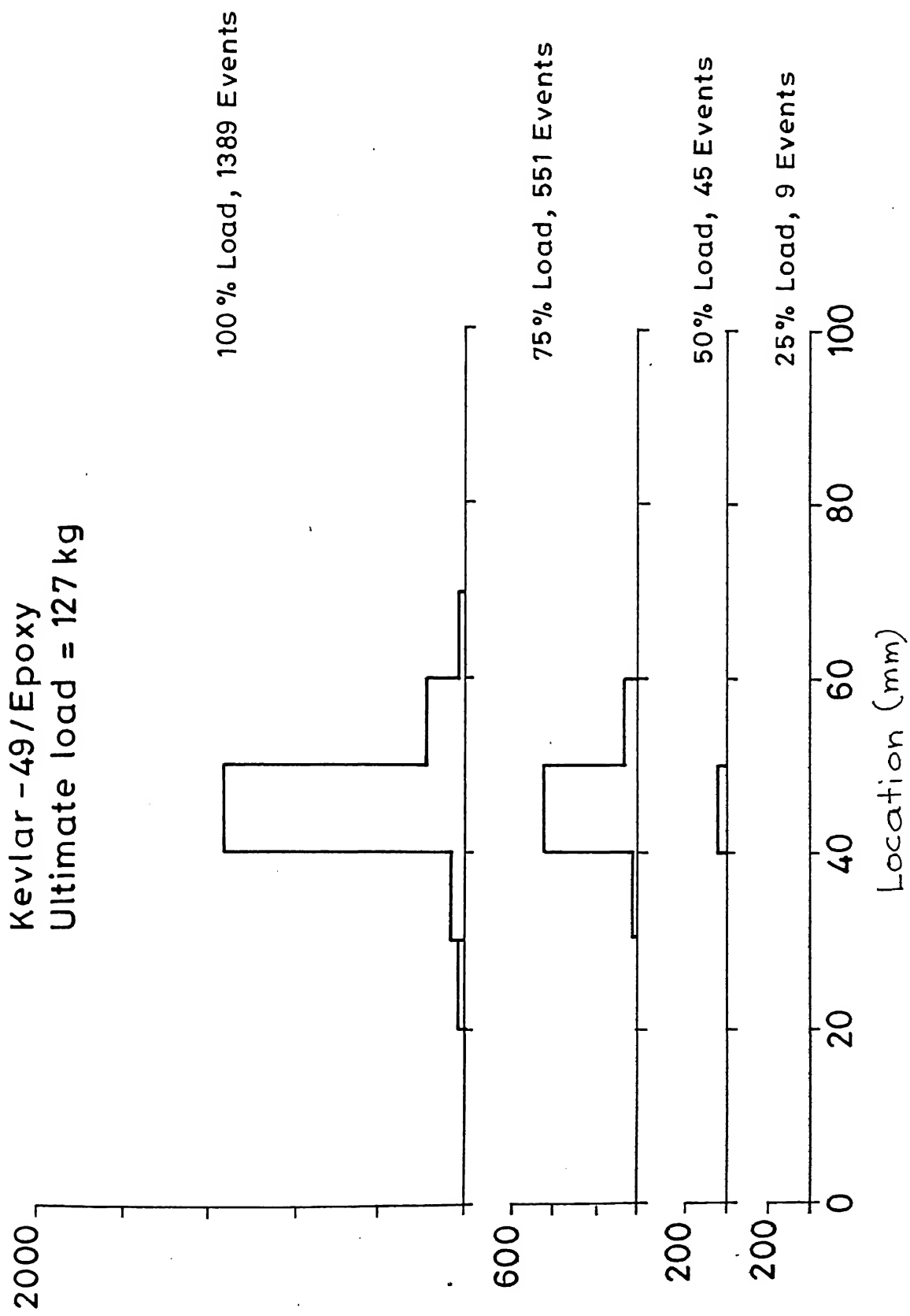


Fig. 5.3 Distribution of events vs location (LOC) of [90<sub>12</sub>] - laminate.

area.

An observation of the histograms at various load levels (25%, 50%, 75%, 100%) of the different laminates also confirms the fact that in the case of  $90^\circ$  and  $45^\circ$ -laminates the damage occurs predominately towards the later portion of the load whereas in the case of  $0^\circ$ -laminate the damage occurs steadily from 50% of the load onwards.

Fig 5.4, 5.5 and 5.6 present the histograms based on peak amplitude (PA) of the three unidirectional laminates. Comparing the various histograms, the damage in  $90^\circ$ -laminate seems to generate more events with lower peak amplitude than  $45^\circ$ -laminate or  $0^\circ$ -laminate. According to literature lower amplitude events (around 40-45 dB) correspond to matrix damage. The  $45^\circ$ -laminate damage generated fairly good number of events with medium range (50-75 dB) and also at higher peak amplitudes. This indicates the damage may also be due to other mechanisms such as delamination, friction, splitting and of course fiber breaks. The classification of damages, in the present analysis, based on peak amplitude has become difficult because of three facts : 1) the reinforcement being in the fabric form the damage propagation in  $90^\circ$  and  $45^\circ$  laminates also involve fiber breaks and probably splits and other mechanisms. 2) the steps in PA as shown in the figures are quite big (10 dB) and as such the analysis is not very fine, and 3) the number of samples tested were only a few. Since the present work is envisaged at an attempt to determine the detailed test procedure and methodology for such an analysis, at present no definite conclusions can be

Kevlar - 49 / Epoxy  
Ultimate load = 1166 kg

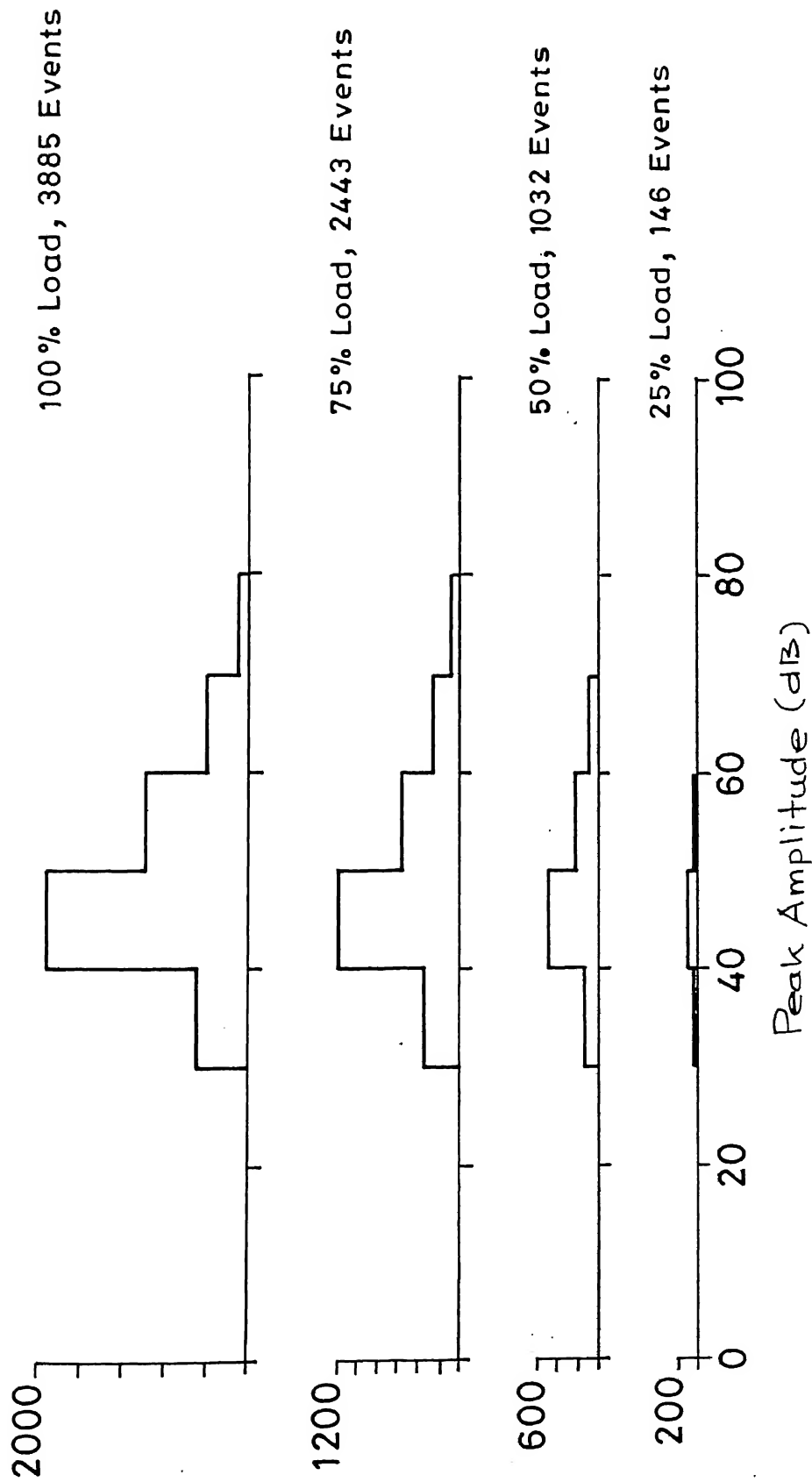


Fig. 5.4 Distribution of events vs peak amplitude (PA) of [0<sub>12</sub>] - laminate.

Kevlar-49/Epoxy  
Ultimate load = 148 kg

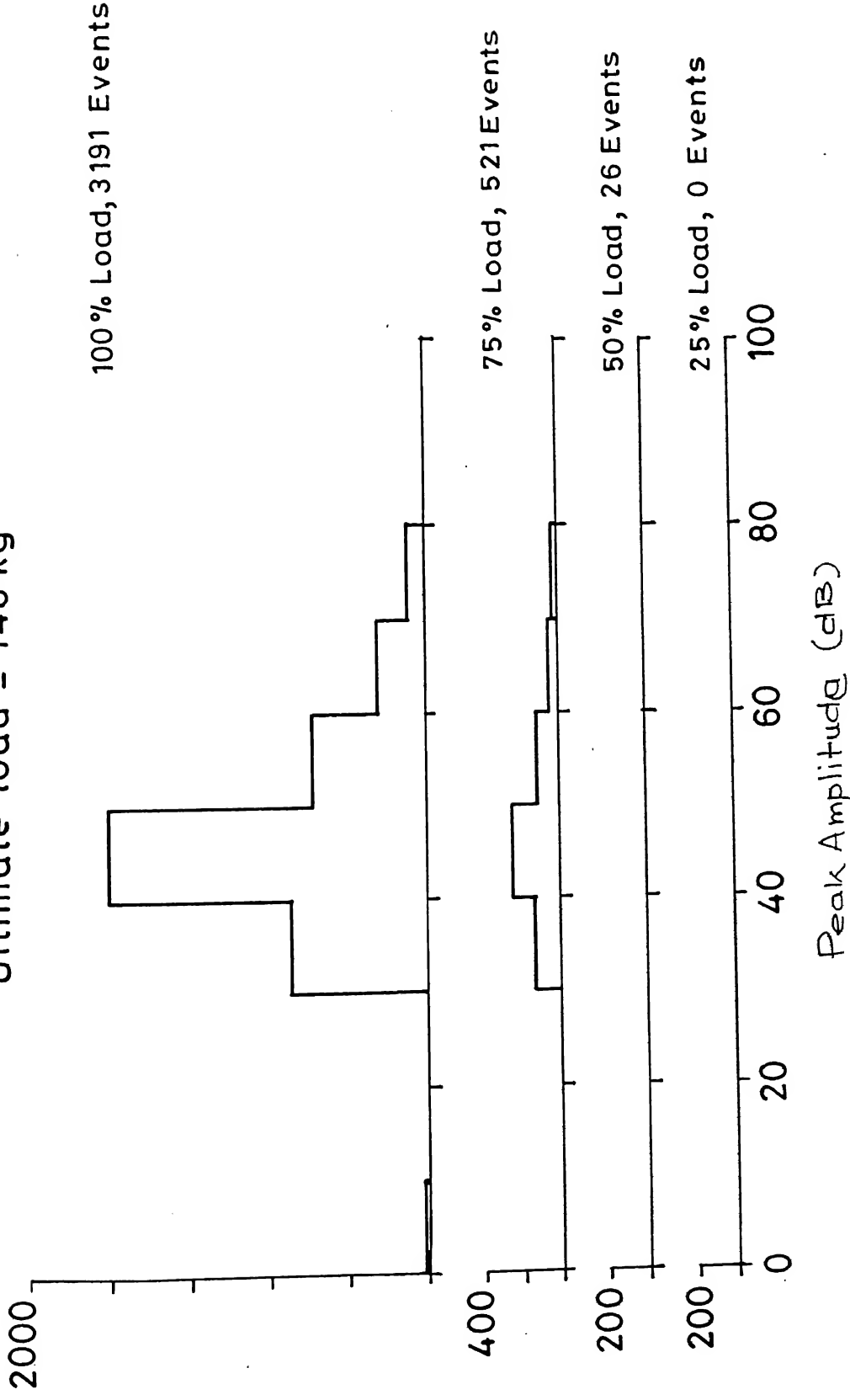
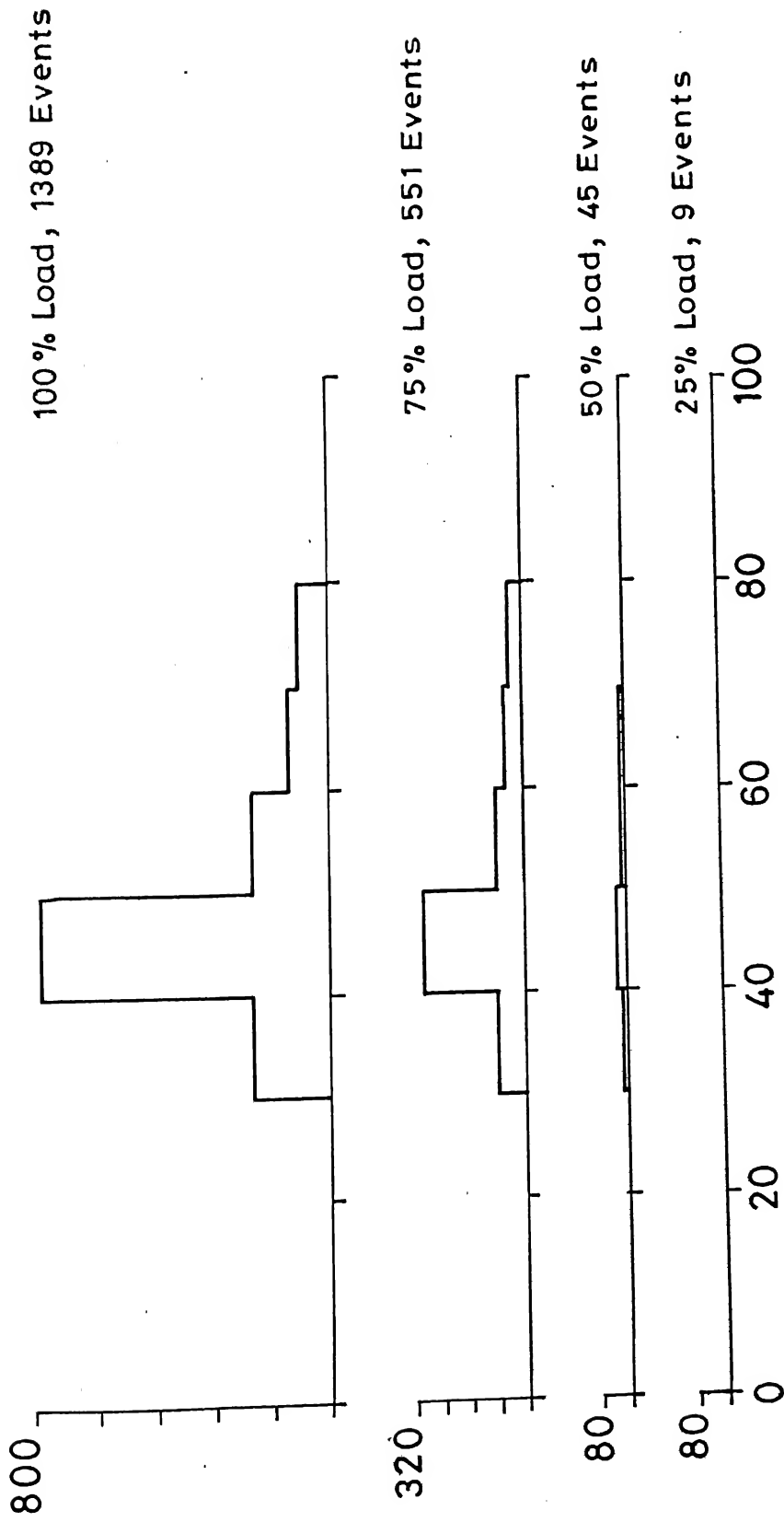


Fig. 5.5 Distribution of events vs peak amplitude (PA) of  
[45]<sub>12</sub> - laminate.

Kevlar-49 / Epoxy  
Ultimate load = 127 kg



Peak Amplitude (dB)

Fig. 5.6 Distribution of events vs peak amplitude (PA) of  
[90<sub>12</sub>] - laminate.

drawn and a more exhaustive analysis is warranted (planned).

Fig. 5.7 - 5.9 present a more important analysis in the form of histograms based on event duration (ED) of the various unidirectional laminates. A comparison of the various histograms shows that the events in  $90^{\circ}$ -laminate are predominantly with low ED whereas those in the case of  $0^{\circ}$ -laminate have significant percentage with higher values of ED and the behaviour of  $45^{\circ}$ -laminate damage is in between the two. This observation agrees with the fact that the events of matrix related damage have lower ED compared with fiber related damage. Another worthy observation is that as the load is increased in  $90^{\circ}$ -laminate the events with low ED continue to occur in the same proportion showing that the matrix failure continues to dominate. In the case of  $0^{\circ}$ -laminate events with lower ED occur at lower load level followed by events with lower and higher ED as the load is increased. This may indicate in the case of  $0^{\circ}$ -laminate the matrix damage precedes fiber damage. As explained in the previous paragraph the damage in the case of  $90^{\circ}$ -laminate also consisted some amount of fiber breaks.

The data of cross-ply laminates are presented in Fig. 5.10 - 5.15. Fig. 5.10 and 5.11 show the location histograms of  $[0_3/90_3]_S$  and  $[90_3/0_3]_S$  laminates. From these it may be observed that the damage is more wide spread around the notch region in  $[90/0]_S$  laminate than in  $[0_3/90_3]_S$ -laminate. This seems to be the same at all load levels. Also at ultimate load the damage spread to farther points in the case of  $[0/90]_S$  laminate than in  $[90/]_S$  -laminate. As mentioned earlier the analysis is still

Kevlar - 49 / Epoxy  
Ultimate load = 1166 kg

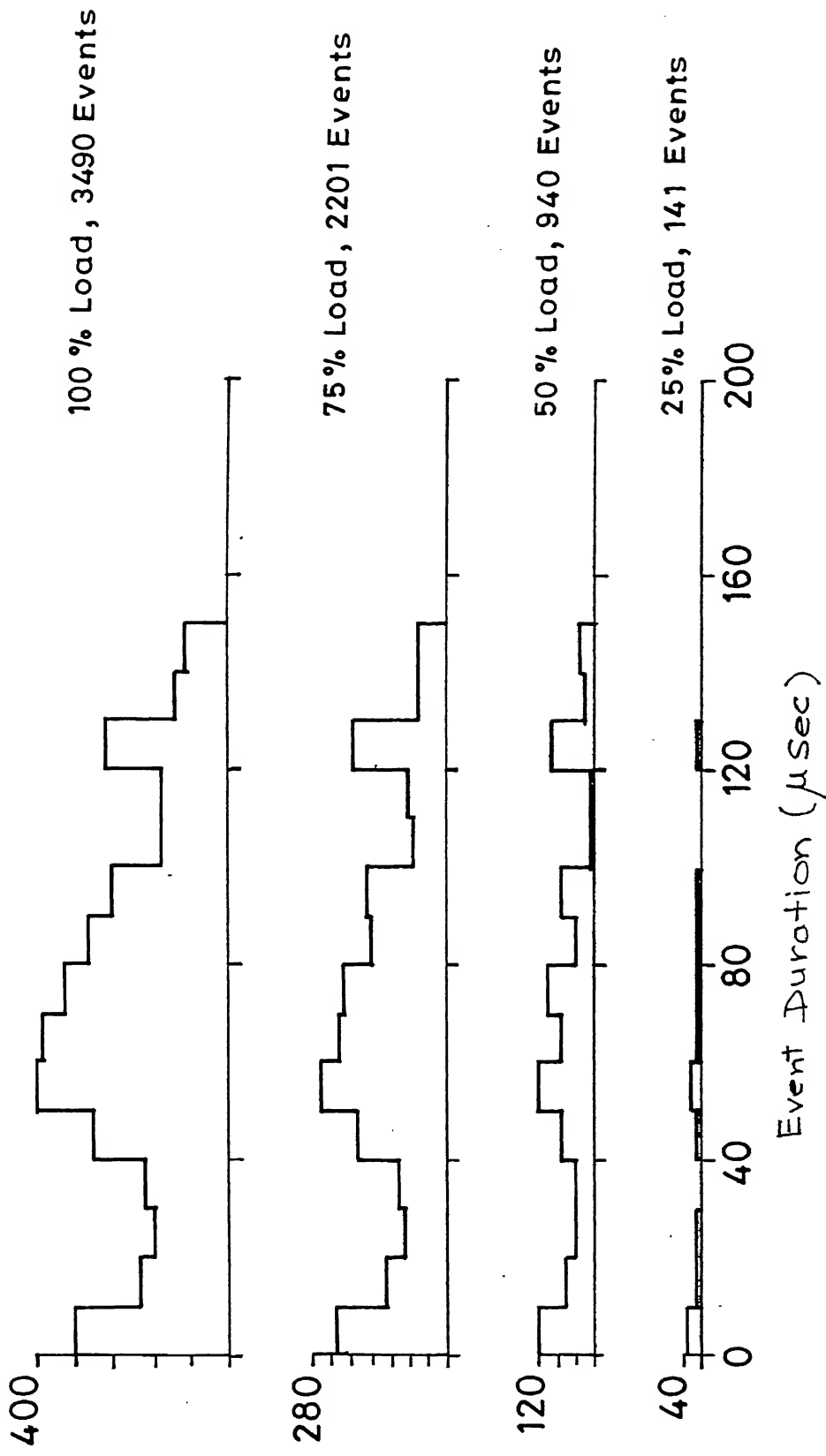


Fig. 5.7 Distribution of events vs event duration (ED) of [0<sub>12</sub>]-laminates.

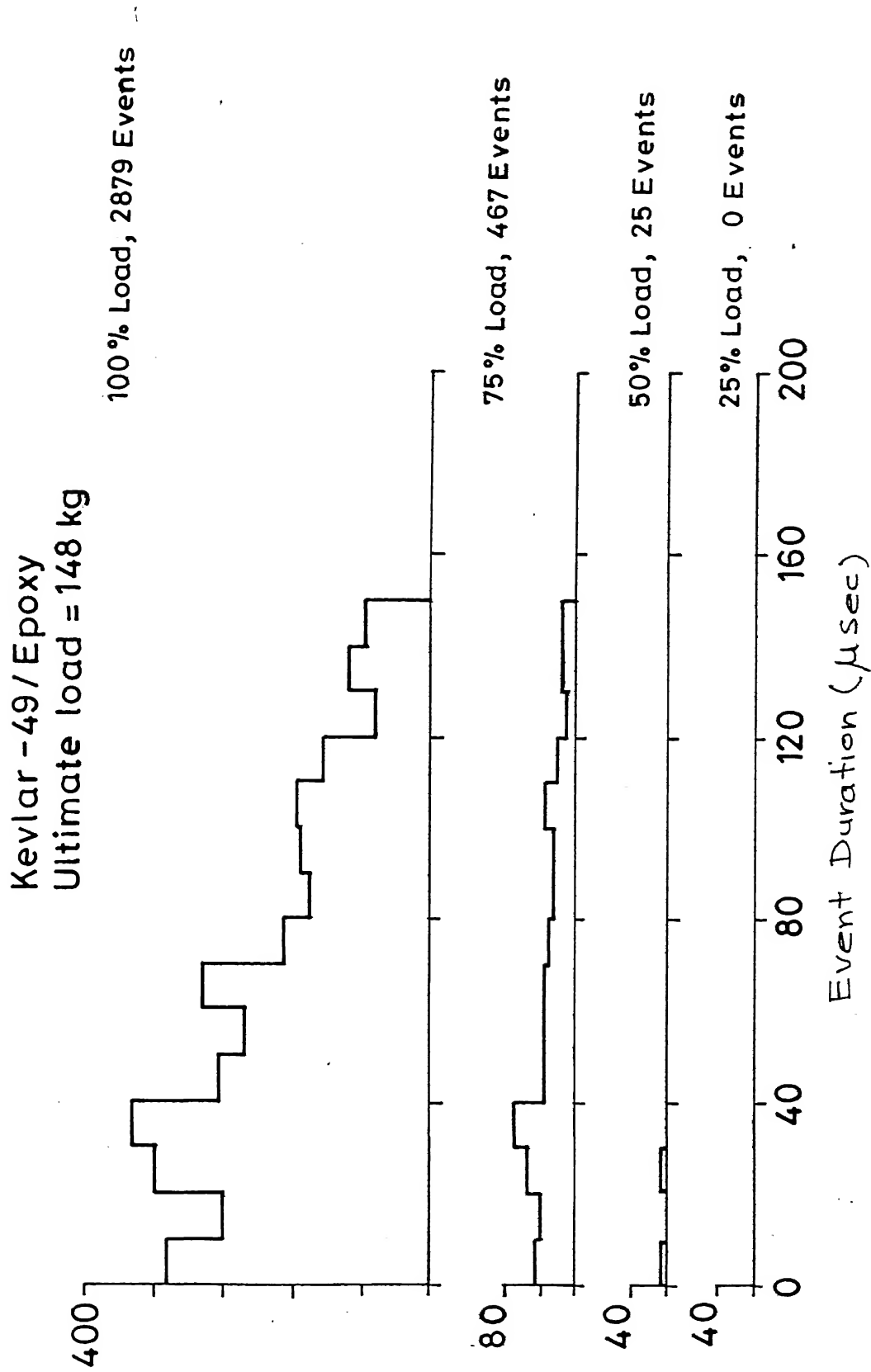


Fig.5.8 Distribution of events vs event duration (ED) of [45<sub>12</sub>]- laminate.

Kevlar-49/Epoxy  
Ultimate load = 127 kg

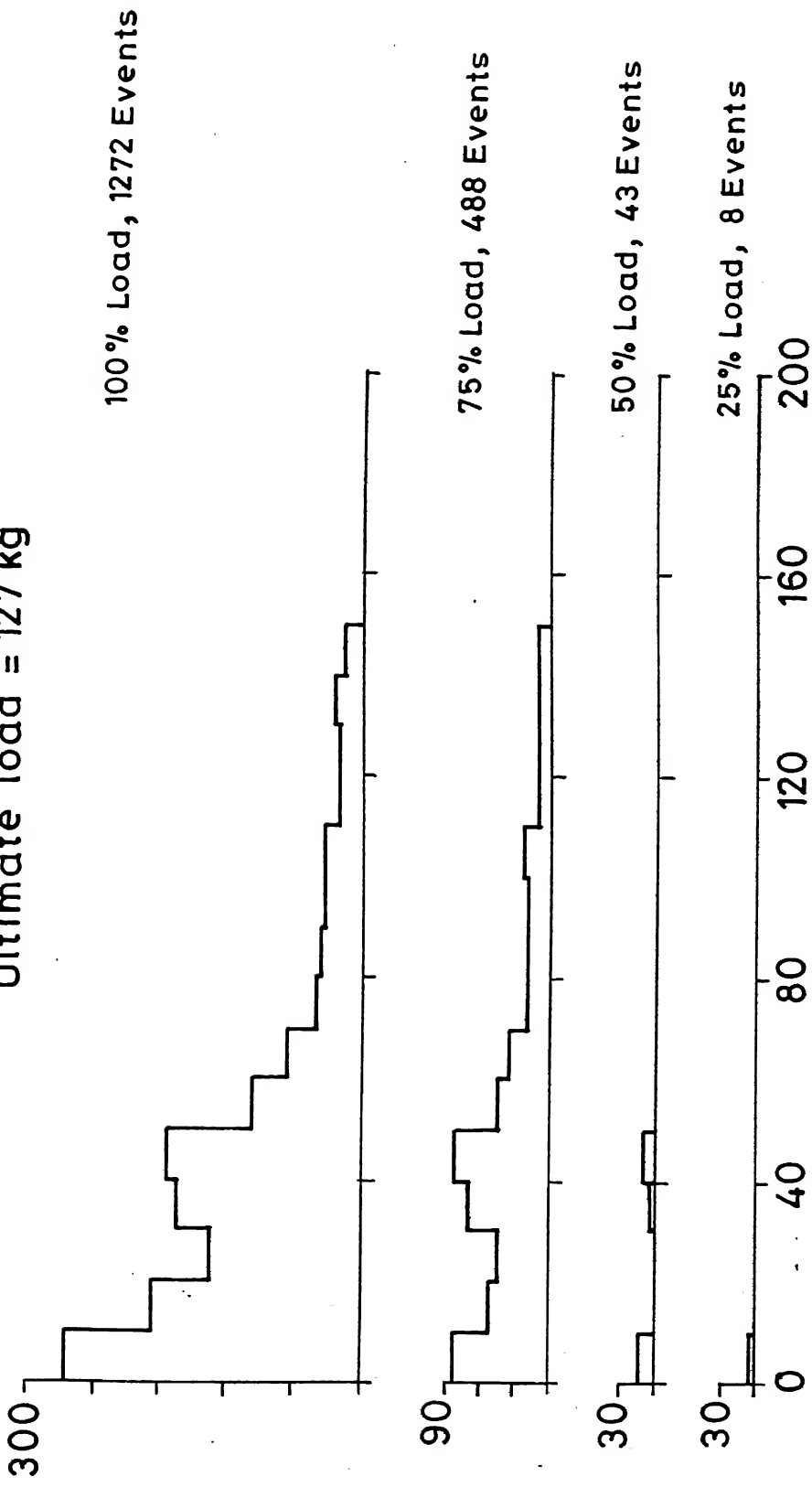


Fig.5.9 Distribution of events vs event duration (ED) of [90<sub>12</sub>] - laminate .

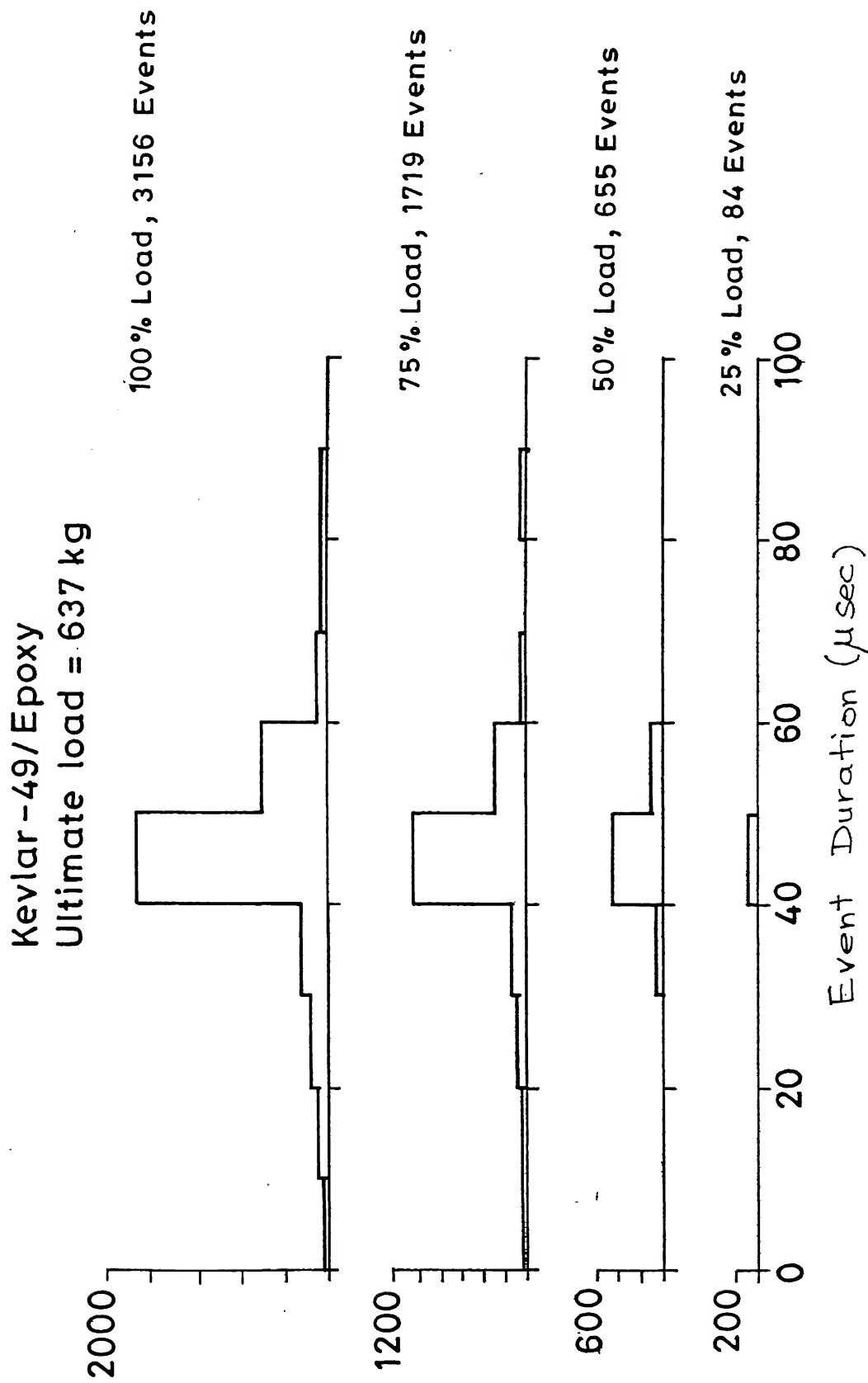


Fig. 5.10 Distribution of events vs location (LOC) of  $[\text{O}_3 / 90_3]_s$ -laminates.

coarse as the total distance between sensors was divided into only 10 steps.

The histograms based on peak amplitude (PA) can be found in Fig. 5.12 and 5.13. The data seems to be inadequate to draw any conclusions except to observe that events with high PA start coming from a lower load in the case of  $[0/90]_S$  than in the case of  $[90/0]_S$ -laminate. A similar trend can be clearly observed in the histograms plotted with respect to ED, Fig. 5.14 and 5.15, for the two types of cross-ply laminates. The AE events in  $[0/90]_S$  laminate consist significant amount of events with higher ED than in  $[90/0]_S$ -laminate in which there is more concentration towards the lower end of ED scale. This suggests that more damage takes place in unsupported outer layers.

Kevlar-49/Epoxy  
Ultimate load = 637 kg

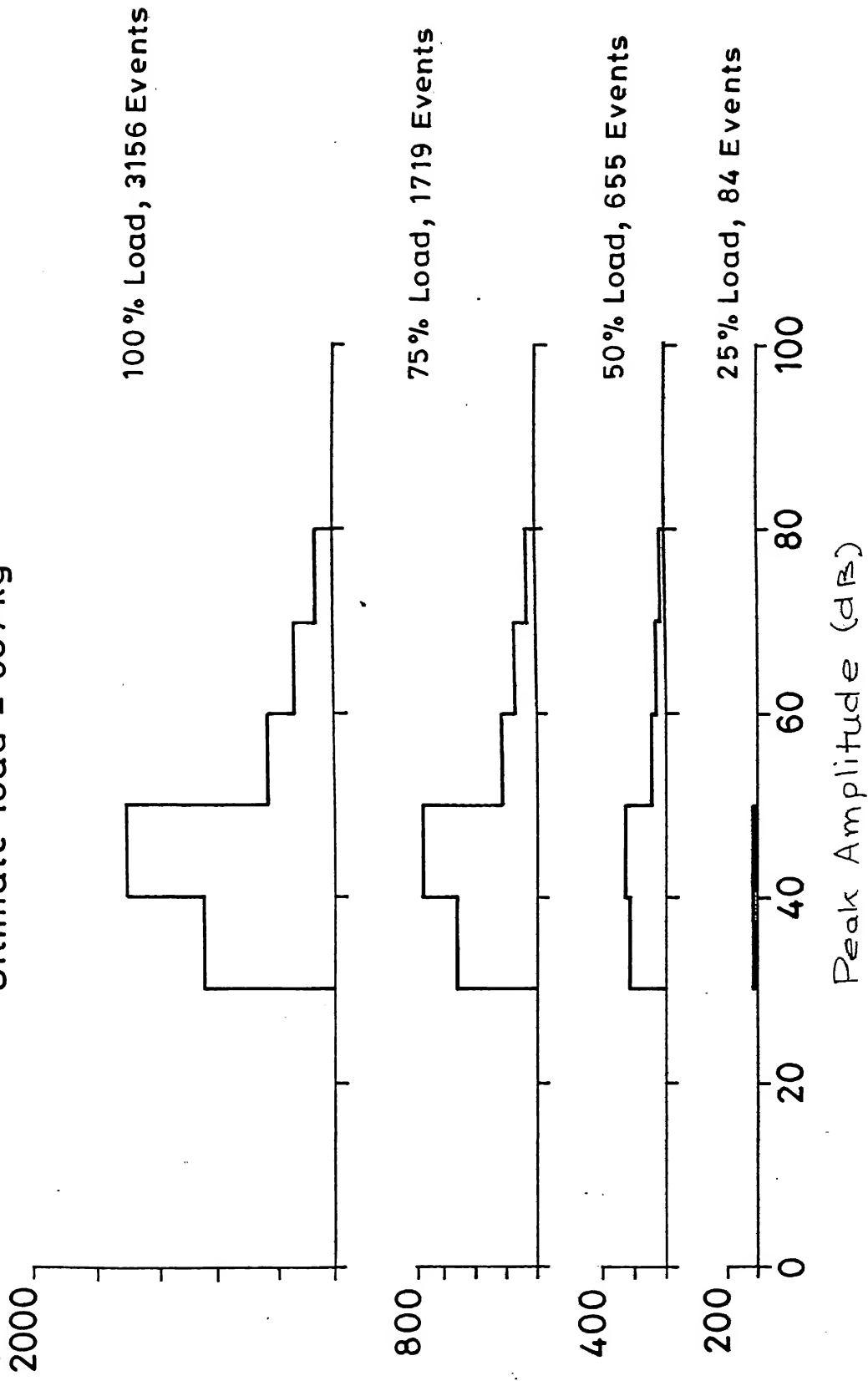


Fig. 5.12 Distribution of events vs peak amplitude (PA) of  $[0_3/90_3]_s$  - laminate.

Kevlar-49/Epoxy  
Ultimate load = 702 kg

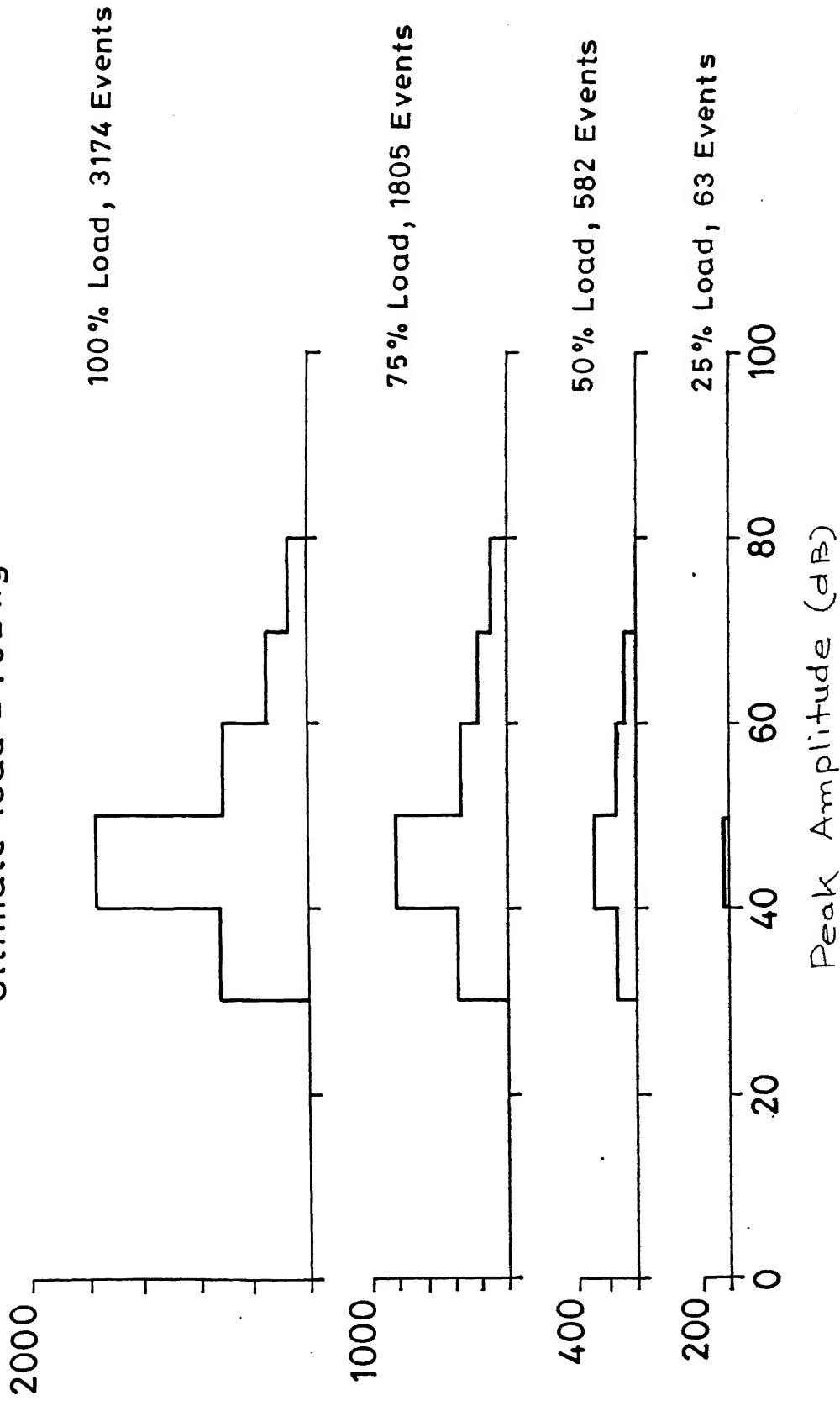


Fig. 5.13 Distribution of events vs peak amplitude (PA) of  $[90_3/O_3]_s$  - laminate.

Kevlar-49/Epoxy  
Ultimate load = 637 kg

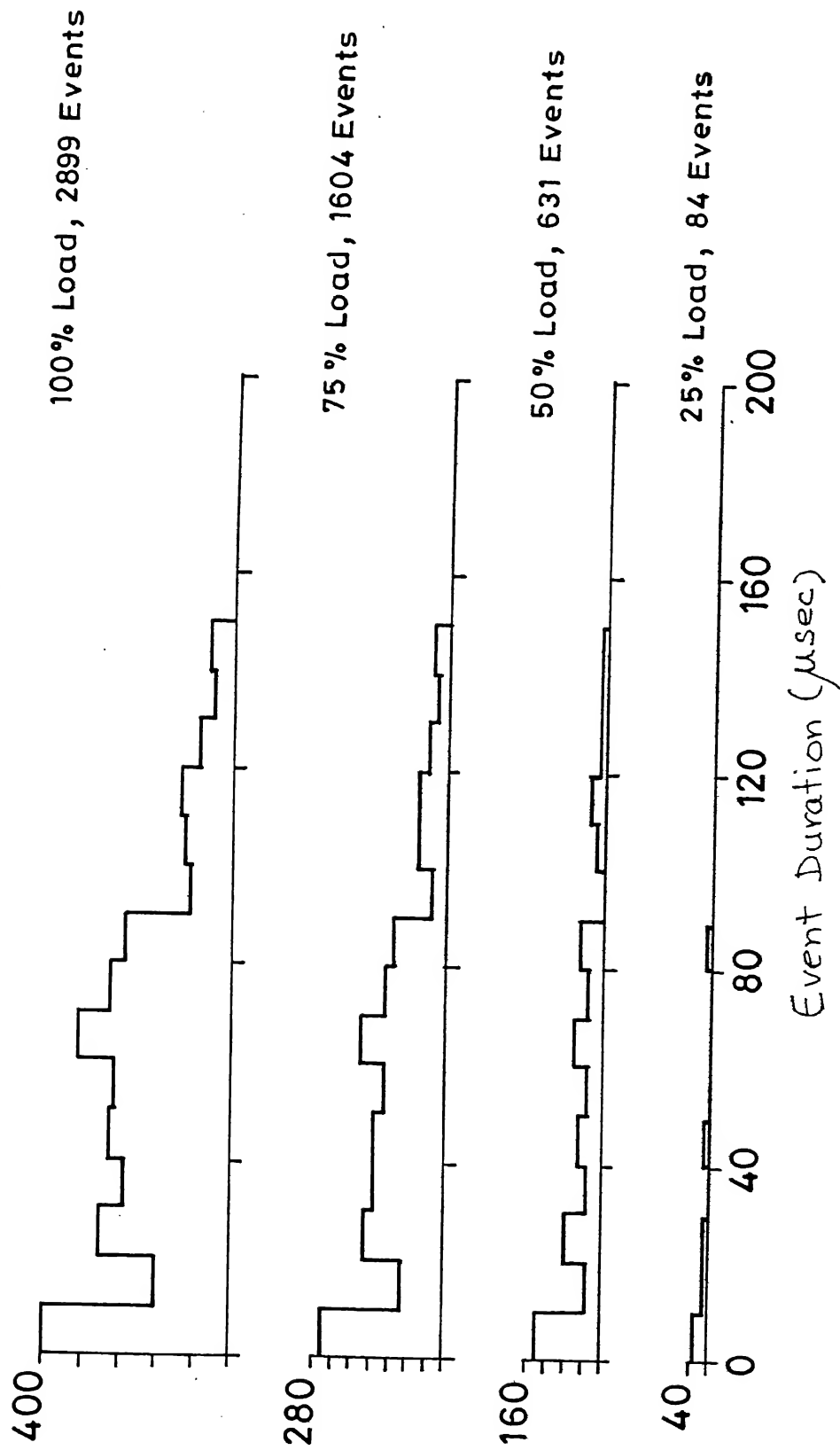


Fig. 5.14 Distribution of events vs event duration (ED) of  $[O_3/90_3]_s$  - laminate.

Kevlar -49/Epoxy  
Ultimate load = 702 kg

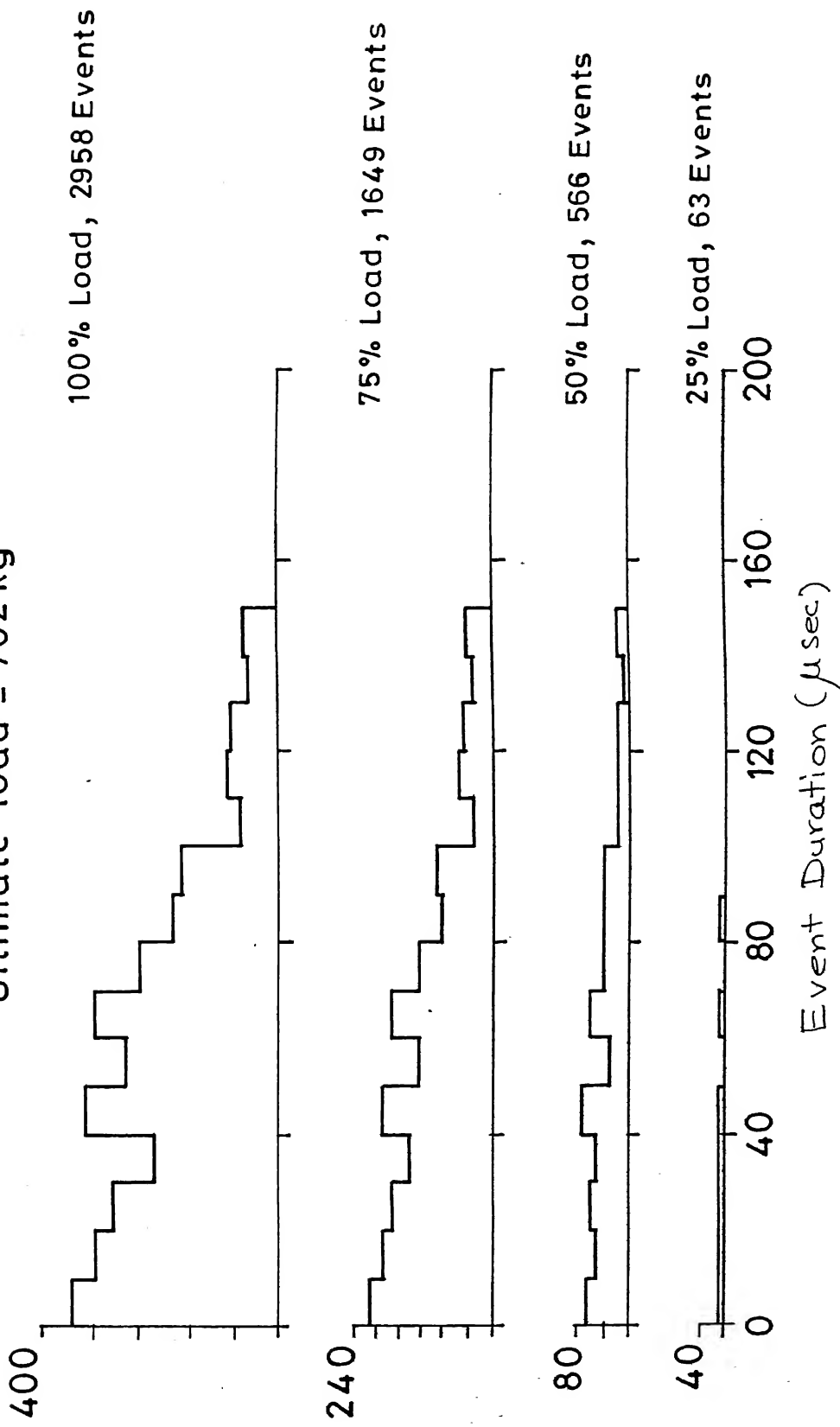


Fig. 5.15 Distribution of events vs event duration (ED) of  $[90_3/0_3]_s$  - laminate.

## CHAPTER 6

### CONCLUSIONS

Preliminary studies of damage propagation in Kevlar fabric reinforced epoxy composite has been made. The experimental study was done using Acoustic Emission. The study has been conducted on unidirectional laminates of  $0^\circ$ ,  $90^\circ$ , and  $45^\circ$  - configurations and cross-ply laminates  $[0_3/90_3]_s$  and  $[90_3/0_3]_s$ . Based on the observations made the following conclusions can be drawn:

1) The damage in the  $90^\circ$ - unidirectional laminate is very localized and occurs just before the ultimate failure. The damage in the case of  $0^\circ$ -laminate will be complex and spreads more around the notch.

2) Event Duration histogram can be an effective means in understanding the damage mechanisms related matrix and fiber.

3) Though peak amplitude histogram is also supposed to be a good parameter in understanding the damage mechanisms, with regard to Kevlar composites the conclusions are only qualitative and more in-depth analysis is required.

#### 6.1 SCOPE FOR FUTURE WORK :

The present work has laid emphasis on the development of a methodology to monitor damage in Kevlar/epoxy composites using AE technique. The future scope of work lies in the identification of different failure mechanisms, determining damage criticality and establishing correspondance between AE

event parameters and the specific failure processes. Events corresponding to a specific failure process, plotted on a hypothetical six dimensional space with six AE parameters forming the axes of such a space, are likely to form a cluster. It is needed to test large and adequate number of samples to identify these clusters thereby establishing correspondance between AE intensities and specific failure processes.

The developed software for AE data handling can be extended to plot three-dimensional plots to get a better insight and to corelate several parameters together. The software can be extended to incorporate facilities like statistical analysis of the accumulated data.

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



## APPENDIX A

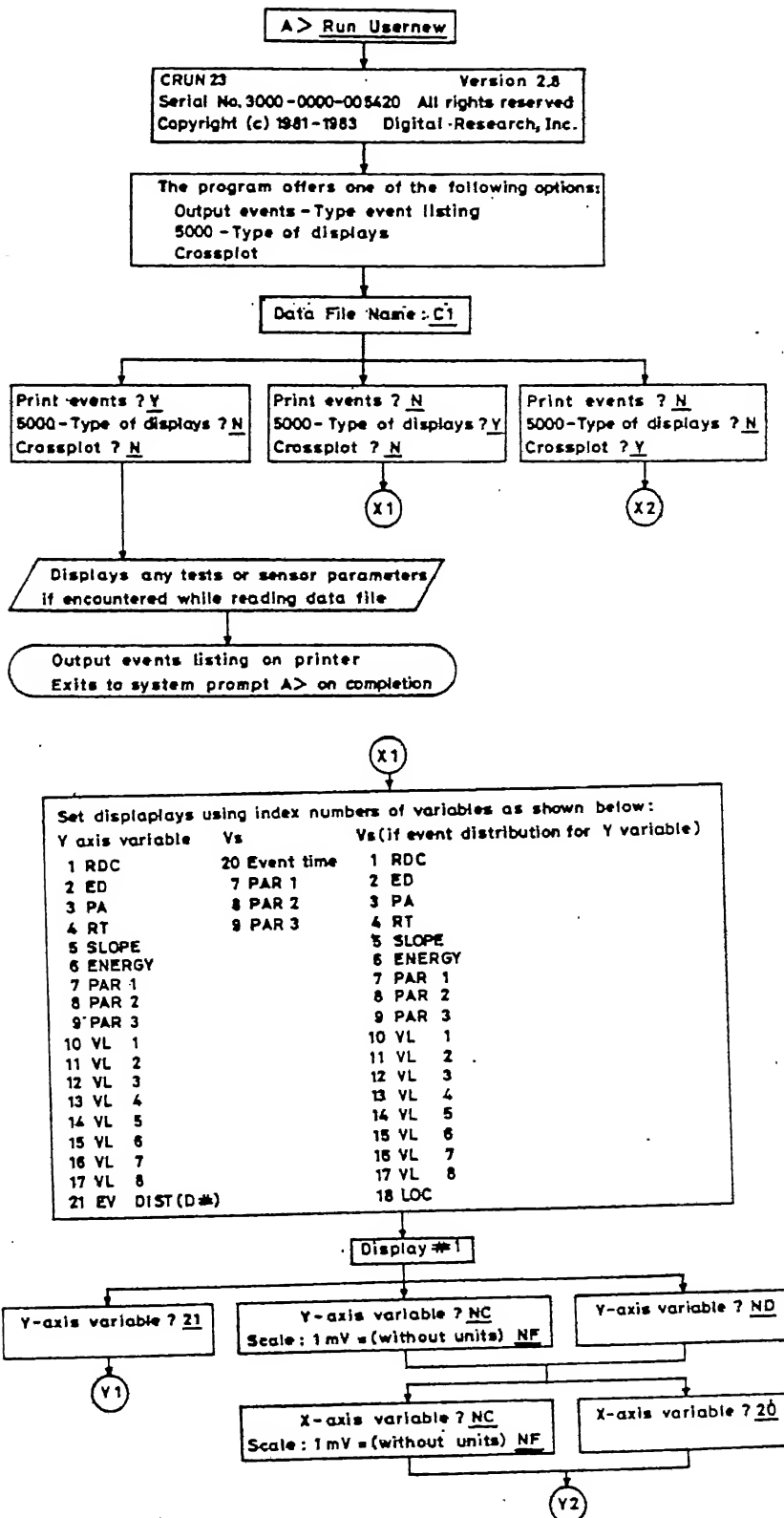
FLOWCHART : Possible replies to various prompts during usernew execution

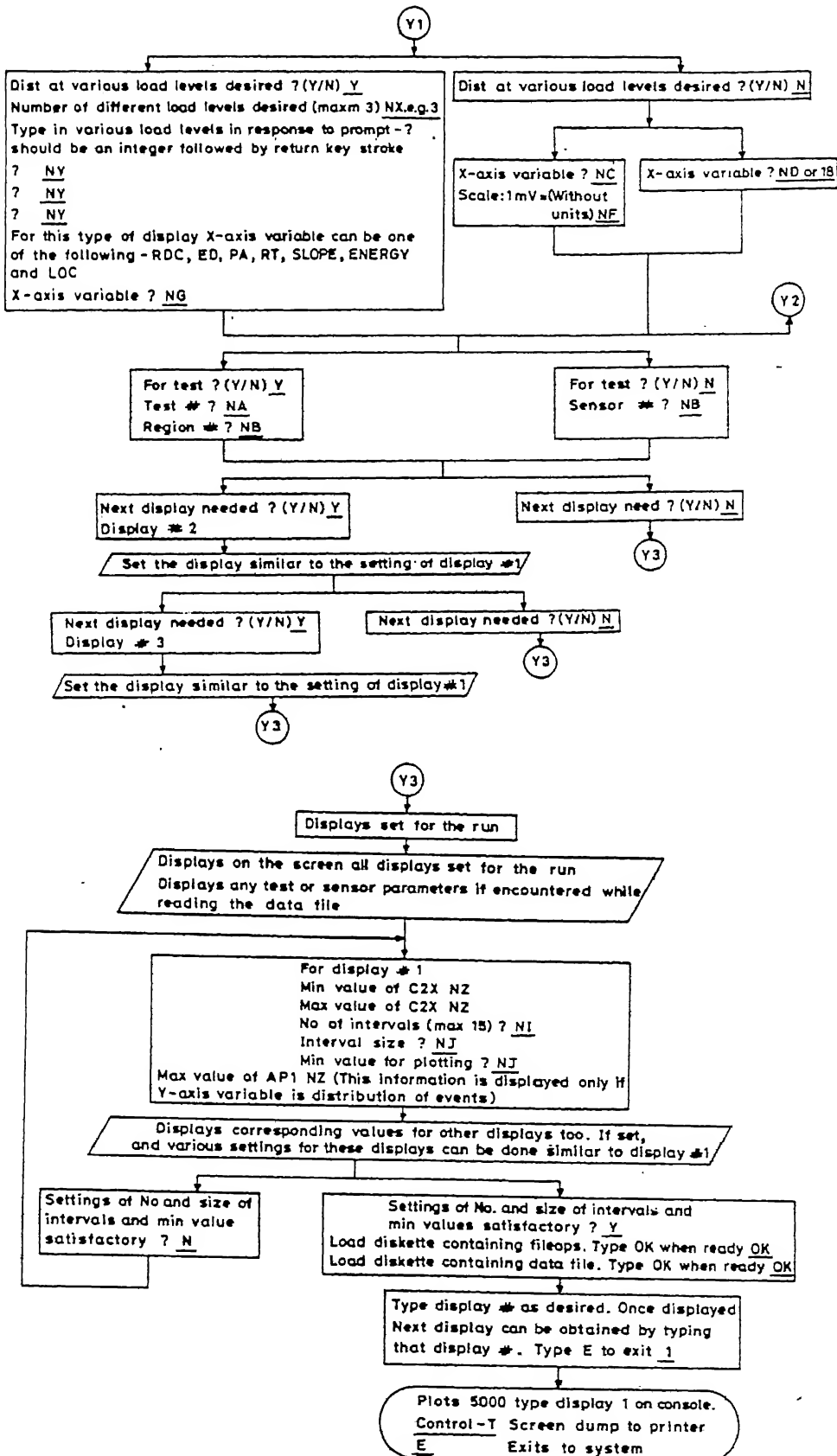
### Variables used in Flowchart :

- C1 - Name of the data file e.g. Z.D01.
- C2X - Name of the variable set for the X-axis of a particular display.
- C2Y - Name of the variable set for the Y-axis of a particular display
- CX - ON or OFF
- NA - A number between 1 and 4 (Integer value)
- NB - A number between 1 and 8 (Integer value)
- NC - A number between 7 and 9 (Integer value)
- ND - A number between 1 and 6 or 10 and 17 (Integer value)
- NE - ND or 18 or 20 or 22 (Integer value)
- NF - Relevant value to convert analog parameter to a Physical Quantity.
- NG - A number between 1 and 6 or 18 (Integer value)
- NH - A number between 1 and 3 not exceeding the number of displays set during a run or E.
- NI - A number between 1 and 15
- NJ - Any relevant value depending on plotting requirements
- NX - A number between 1 and 3 (Integer value)
- NY - A number between 0 and 100 (Integer value)
- NZ - Relevant value as found from data file

### Code used in the flowchart

-  What program displays on advantage screen
-  Possible replies to the prompts (under scored)
-  Note / Comments
-  Program output





(X2)

Set crossplot using index number of variables as shown below

1 RDC  
2 ED  
3 PA  
4 RT  
5 SLOPE  
6 ENERGY  
7 PAR 1  
8 PAR 2  
9 PAR 3  
10 VL 1  
11 VL 2  
12 VL 3  
13 VL 4  
14 VL 5  
15 VL 6  
16 VL 7  
17 VL 8  
18 LOC  
20 EVENT TIME  
22 EVENTS

X-axis variable ? NC

Scale: 1mV = (without units) NF

X-axis variable ? NE

Y-axis variable ? NC

Scale: 1mV = (without units) NF

Y-axis variable ? NE

For test ? (Y/N) Y

Test # ? NA

Region # ? NB

Line drawing ? (ON/OFF) CX

For test ? (Y/N) N

Sensor # ? NB

Line drawing ? (ON/OFF) CX

Crossplot set for the run

C2Y Vs C2X test # NA Region # NB

Crossplot set for the run

C2Y Vs C2X Sensor # NB

Displays any test or sensor parameters if encountered while reading data file

Load diskette containing fileops. Type OK when ready OK

Load diskette containing data file. Type OK when ready OK

Plots crossplot on console

Control - T Screen dump on printer

E Exits to system prompt A>

# APPENDIX B

## Sample dialogue

UN USERNEW

```
-----
RUN23                               Version 2.8
erial No. 3000-0000-005420        All rights reserved
opyright (c) 1981-1983          Digital Research, Inc.
-----
```

THE PROGRAM OFFERS ONE OF THE FOLLOWING OPTIONS:  
 'OUTPUT EVENTS'--TYPE EVENT LISTING  
 5000--TYPE OF DISPLAYS  
 CROSSPLOT

DATA FILE NAME: Z.D01

PRINT EVENTS? N

000--TYPE OF DISPLAYS? Y

CROSSPLOT? N

ET DISPLAYS USING INDEX NUMBERS OF VARIABLES AS SHOWN BELOW:

AXIS VARIABLE	VS	VS (IF EVENT DISTRIBUTION FOR Y VARI
1 RDC	20 EVENT TIME	1 RDC
2 ED	7 PAR 1	2 ED
3 PA	8 PAR 2	3 PA
4 RT	9 PAR 3	4 RT
5 SLOPE		5 SLOPE
6 ENERGY		6 ENERGY
7 PAR 1		7 PAR 1
8 PAR 2		8 PAR 2
9 PAR 3		9 PAR 3
10 VL 1		10 VL 1
11 VL 2		11 VL 2
12 VL 3		12 VL 3
13 VL 4		13 VL 4
14 VL 5		14 VL 5
15 VL 6		15 VL 6
16 VL 7		16 VL 7
17 VL 8		17 VL 8
21 EV DIST(D#)		18 LOC

DISPLAY # 1

AXIS VARIABLE? 21

IST AT VARIOUS LOAD LEVELS DESIRED ?(Y/N) Y

NUMBER OF DIFFERENT LOAD LEVELS DESIRED(MAXM 3) 3

TYPE IN VARIOUS LOAD LEVELS IN RESPONSE TO PROMPT--?

SHOULD BE AN INTEGER FOLLOWED BY RETURN KEY STROKE

25

50

75

OR THIS TYPE OF DISPLAY X AXIS VARIABLE CAN BE ONE

OF THE FOLLOWING - RDC,ED,PA,RT,SLOPE,ENERGY & LOC

AXIS VARIABLE? 3

OR TEST? (Y/N) Y

TEST #? 1

REGION #? 3

NEXT DISPLAY NEEDED ?(Y/N) Y

DISPLAY # 2

AXIS VARIABLE? 21

IST AT VARIOUS LOAD LEVELS DESIRED ?(Y/N) N

NEXT DISPLAY NEEDED ?(Y/N) Y

DISPLAY # 3

Y AXIS VARIABLE? 6

X AXIS VARIABLE? 20

FOR TEST? (Y/N) Y

TEST #? 1

REGION #? 13

DISPLAYS SET FOR THE RUN

1 DIST OF EVENTS VS PA

TEST # 1

REGION #

2 DIST OF EVENTS VS RDC

TEST # 1

REGION #

3 ENERGY VS EVENT TIME

TEST # 1

REGION #

FOUND PARAMETERS FOR TEST 1 , ID = T1

RECORDED 05/24/83 AT 14:44:47 BY SYSTEM LEVEL ODO3

SENSORS: 1 3 4

REGION LOW HIGH

1 100 199

2 200 499

3 500 1000

SEN1	SEN2	LOC1	LOC2	DT
4	1	100	300	100
1	3	300	1000	500

	MIN	MAX
RDC	1	100
ED	1400	1599
PA	0	64
RT	0	65520
SLOPE	0	65520
ENERGY	0	111
PAR 1	0	10240
PAR 2	0	10240
PAR 3	0	10240

FOR DISPLAY # 1

MIN VALUE OF PA 23

MAX VALUE OF PA 24

NO OF INTERVALS (MAX 15)? 2

INTERVAL SIZE ? 1

MIN VALUE FOR PLOTTING ? 22

MAX VALUE OF AP1 30

FOR DISPLAY # 2

MIN VALUE OF RDC 61

MAX VALUE OF RDC 80

NO OF INTERVALS (MAX 15)? 10

INTERVAL SIZE ? 2

MIN VALUE FOR PLOTTING ? 60

FOR DISPLAY # 3

MIN VALUE OF EVENT TIME 0.74

MAX VALUE OF EVENT TIME 7.97

NO OF INTERVALS (MAX 15)? 0.515

INTERVAL SIZE ? 0.5

MIN VALUE FOR PLOTTING ? 0.5

SETTINGS OF NO & SIZE OF INTERVALS & MIN VALUE SATISFACTORY ? Y